Implementation of the Passive House Standard in UK Housing

Assessing the Impact on Future Energy Consumption and Carbon Dioxide Emissions

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by

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Abstract

With the threat of global warming reaching a tipping point, the UK have set themselves the ambitious target of reducing CO_2 emissions by at least 60% by 2050 as compared to 1990 levels. In the built environment, current design criteria focus on reducing operational energy demand and are based on climate data observed over the past two decades.

This study tries to establish what impact constructing to the Passive House standard would have on both energy demand and CO_2 emissions of the UK housing stock. Based on a specific new-build Passive House it is looking beyond today's thermal performance. This is done by predicting total heating and cooling demand over the lifetime of the building using dynamic thermal modelling that takes into account forecasted future climate change. Furthermore, this study investigates the impact that passive design measures such as thermal mass and shading would have over the lifetime of the building, based on heating and cooling energy demand, as well as embodied energy.

It was found that passive design measures were very effective in reducing cooling energy demand. They are predicted to lead to an overall reduction of CO_2 emissions due to heating and cooling of up to 50%. However, it was also found that the materials selected for the passive design measures do have a significant impact on the total CO_2 emissions over the lifetime of the building, including both operational and embodied energy.

Overall, the Passive House standard was found to be an effective tool for achieving the UK's CO_2 reduction target. However, the results of this study show that embodied energy and embodied CO_2 have to be taken into consideration in the CO_2 calculation. It is concluded that besides Building Regulations controlling operational energy demand, more emphasis needs to be given to material selection.

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List of Terms and Abbreviations

C&C	Contraction & Convergence
CDD	Cooling Degree Days
CEPHEUS	Cost-Efficient Passive House as European Standard
CO_2	Carbon dioxide

COP	Coefficient of Performance, describes the energy efficiency of air-conditioning units and heat pumps in heating mode
CSH	Code for Sustainable Homes
DER	Dwelling Emissions Rate, as calculated with SAP
DTR	Department of Transport and the Regions
EAHX	Earth-to-Air Heat Exchanger
EC	European Commission
EER	Energy Efficiency Ratio, describes the energy efficiency of air-conditioning units and heat pumps in cooling mode
Embodied energy	Energy used to produce an item, including the procurement of raw materials, manufacture, transport, maintenance and repair
EPC	Energy Performance Certificate
HDD	Heating Degree Days
HIP	Home Information Pack
ICE	Inventory of Carbon and Energy, published by the University of Bath (Hammond & Jones 2005)
MVHR	Mechanical Ventilation with Heat Recovery
Operational energy	Energy used to operate a building, including heating, cooling, lighting, appliances, services and equipment
PHPP	Passive House Planning Package, software used to design a Passive House
TAS	Thermal Analysis System, dynamic thermal modelling software
TER	Target Emissions Rate, as calculated with SAP
SAP	Standard Assessment Procedure for the assessment of dwellings regarding their energy demand and CO_2 emissions

1 Introduction

Since the beginning of the industrial revolution in the mid 19^{th} century and consequently an immense increase in the burning of fossil fuels has helped mainly the industrialized nations to achieve ever increasing levels of wealth and prosperity. Although warned by a significant group of scientists for many decades, most nations are just now starting to acknowledge their responsibility for anthropologic global warming and climate change, a main contributor being fossil fuel combustion.

It is not only the concern over excessive carbon dioxide (CO_2) emissions released into the atmosphere that put Governments into action. With the world population of some 6.7 billion likely to reach 9 billion by 2050, and some of the highest populated developing countries starting to see significant economic growth, the competition over fossil fuel reserves and other resources have dramatically intensified over the past decade. Even if sustainable living is not on top of every nation's agenda, it is the fear over energy security that has pushed the last doubters into action. Now that the importance of energy efficiency and alternative energy sources is recognised, solutions for achieving them, particularly under the thread of climate change, are desperately needed.

The domestic sector plays a significant role in CO_2 emissions. In the UK, energy consumption by domestic users accounts for more than a quarter of the UK's CO_2 emissions (DEFRA 2007). Overall, construction and operation of the build environment is responsible for more than half of the UK's CO_2 emissions (BERR et al. 2007). It is evident that among other areas, the domestic sector will have to be one of the key players if the very ambitious target of at least 60% CO_2 emission reduction by 2050 compared to 1990 levels is to be achieved.

As the need for energy efficient housing has been recognised, national Building Regulations have been and will be amended to enforce construction standard that will lead to a decrease in operational energy demand. The main focus so far was on the demand for space heating and lighting, and to some degree, prevention of overheating. Considering the Government's target to build only Zero Carbon Homes from 2016, the rethinking of how buildings are built and operated is crucial.

Figure 1 Blomstrandbreen Glacier, Spitzbergen, Norway, picture taken 1922 (left) and 2002 (right) (Greenpeace International 2002)

Building to Passive House standard could significantly contribute to achieving the UK targets. Passive Houses are designed such that due to their super-insulation, high air tightness and avoidance of thermal bridging they are primarily heated 'passively' through thermal gains from solar activity, occupants, lighting and appliances use in the building. This almost eliminates the need for space heating. However, with increasing temperature level due to global warming, the focus is likely to shift from reducing heating demand to avoidance of overheating in the summer, and therefore to reducing cooling demand. Furthermore, as operational energy demand is minimised, the relative importance of energy embodied in the materials increases. The question is: Where lies the biggest CO_2 emission savings, in operational energy savings or in the reduction of embodied energy?

Based on a case study, this research explores the impact that thermal mass and other passive design measures have on energy demand and CO_2 emissions for dwellings build to Passive House standard, taking into account both operational and embodied energy. It is focusing on "future-proofing" the buildings, analysing the thermal conditions and operational energy demands that are likely to occur under future climatic conditions as predicted today over the lifetime of the building.

2 Climate Change and the Built Environment

2.1 Climate Change, Global Warming and Human Responsibility

Climate change refers to the variation in the Earth's global climate or in regional climates over time. These variations can be caused by processes internal to the earth (e.g. volcanic activity), external forces (e.g. variations in sunlight intensity) or, more recently, human activities. Climate change has recently become a hot topic as more and more evidence points towards anthropogenic impacts as the main contributor to today's climate change, and global warming in particular (IPCC 2007;Solomon et al. 2007).

Global warming refers to the increase in the average temperature of the Earth's near-surface air and oceans in recent decades and its projected continuation. Climate models referenced by the Intergovernmental Panel on Climate Change (IPCC) predict that global surface temperatures could increase by more than 6℃ between 1990 and 2100, depending on the emissions scenarios used for the climate models. It is further predicted that warming will continue for more than a millennium even if greenhouse gas levels are stabilized (Solomon, Qin, M.Manning, Z.Chen, M.Marquis, K.B.Averyt, M.Tignor, & H.L.Miller (eds.) 2007).

Table 1 UK and world CO_2 emissions

UK and World Emissions 2005	Emissions (MtCO2 per annum)	Percentage of world emissions	Population (million)	Percentage of world population	tCO2/capita per annum	Ratio to world average
UK	564	2%	60	1%	9.55	2.2
Rest of Europe	4,675	14%	529	8%	7.93	1.8
Rest of World	27,636	84%	6,384	92%	4.37	-

The predicted increase in global temperatures is expected to have other side effects, such as sea level rise, more frequent occurrence of heat waves, heavy rainfall, droughts, tropical cyclones and extreme high tides, changes in agricultural yields, glacier retreat (Figure1), species extinctions and disease spread.

Most scientists do agree that the recent steep incline of greenhouse gas concentration in the atmosphere is mainly related to human activities, in particular CO_2 emissions related to fossil fuel combustion. The UK is one of the main contributors to anthropogenic greenhouse gas concentration, particularly when basing it on per capita emissions (Table 1).

2.2 Global Action needed and Meaning for the UK

There is an ongoing global political and public debate regarding what actions should be undertaken to reduce or reverse future global warming.

One approach that is proposed by a number of nations including the European Union is a global framework called 'Contraction & Convergence' (C&C). The theory behind C&C is that in order to stabilise greenhouse gas concentration in the atmosphere, a global emissions limit has to be defined. Based on this limit, each country receives the same per capita emissions allowance. Under this framework, nations would then be able to trade allowances, and high emitters could purchase allowances from those that are emitting less than the limit allows. If C&C was implemented now, high emitting countries such as the UK would have to reduce emissions dramatically, and would have to also buy allowances from low emitters such as most African countries. It remains to be seen whether all major emitting counties can be persuaded to sign up to such agreement.

However, most national governments have signed and ratified the Kyoto Protocol that was negotiated in 1997, aimed at reducing greenhouse gas emissions. Under the protocol, UK had previously agreed to cut its CO_2 emissions by 12.5% compared to the levels of 1990 by 2012. However, following the publication of a number of papers such as the Stern Report (Stern 2006) and the reports from the IPCC in 2007 (Solomon, Qin, M.Manning, Z.Chen, M.Marquis, K.B.Averyt, M.Tignor, & H.L.Miller (eds.) 2007), the UK government have been rethinking their stand. While the IPCC paints a rather gloomy picture of future climate change and its global effect, the Stern Report focused more on the economic implications of climate change. It comes to the conclusion that the future financial consequences of global warming far outweigh the cost of trying to stabilise the current concentration of CO_2 in the atmosphere.

As actions to tackle global warming are implemented at a rather slow pace, global warming to a certain level can not be avoided. Therefore it is equally important to adapt to its expected consequences. The increase in average ambient temperatures has been observed in the UK over the last couple of centuries (Figure 2), and is expected to continue. It is likely that temperature increases will trigger other phenomenon such as increase in intensities and frequencies of storms, flooding and draughts, all having a substantial impact on the build environment.

Last but not least, the recent steep increase in fossil fuel prices due to an ever increasing demand from developed countries, and even more so the developing countries such as China and India, has moved security of fuel supply to the top of Governments' agendas. The efficient use of finite resources, combined with the increased use of renewable sources is their main focus.

2.3 UK Goals and Initiatives

Taking into consideration the above and other studies, the current UK Government intends to go beyond the Kyoto targets and has set its own more stringent targets for reducing CO_2 emissions.

In May of 2007 the Government published the Energy White Paper. It outlines the Government's international and domestic strategy for responding to global warming and security of energy supplies. In the paper the Government states its targets to cut the UK's carbon dioxide emissions by some 60% by about 2050, with real progress by 2020, to maintain the reliability of energy supplies, to promote competitive markets in the UK and beyond, and to ensure that every home is adequately and affordably heated (Department of Trade and Industry 2007).

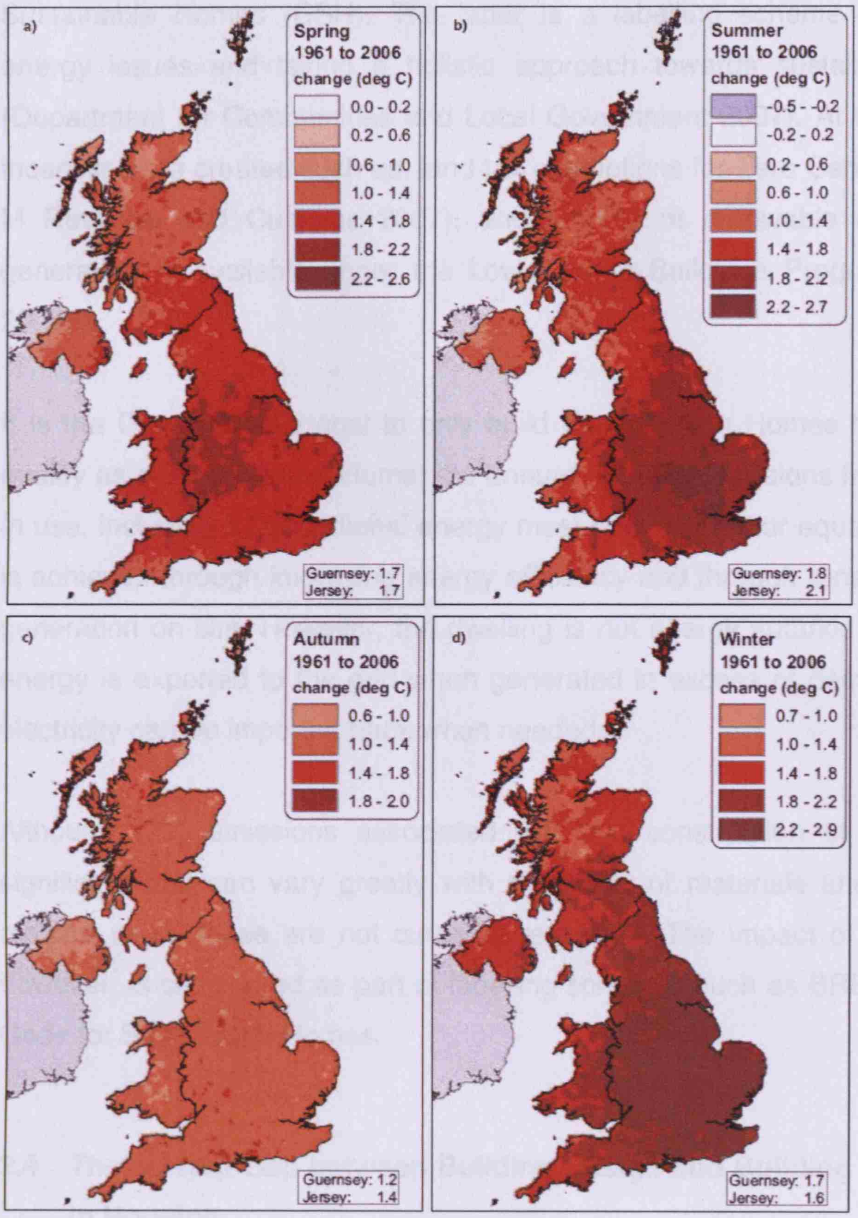


Figure 2 Change in average daily maximum temperature (℃) from 1961 to 2006 based on a linear trend for a) spring, b) summer, c) autumn, d) winter (Jenkins 2007)

The UK's target goes beyond the European Commission's (EC) benchmarks of 20% CO_2 emissions reduction by 2020, and includes the EC's goal of generating 20% of all energy demand with renewable energy by 2020. The UK Government is using various tools to stimulate the process. In the housing sector this includes legislation such as Building Regulations Part L (ODPM 2006), Energy Performance Certificates (EPC) as part of the recently introduced Home Information Packs (HIP) (H M Government 2007), and the Code for

Sustainable Homes (CSH). The latter is a labelling scheme going beyond energy issues and taking a holistic approach towards sustainability issues (Department for Communities and Local Government 2007). At the same time incentives are created such as, land tax exemptions for Zero Carbon Homes (H M Revenue and Customs 2007), and funding of renewable energy micro-generation is available under the Low Carbon Buildings Programme (BERR 2008b).

It is the Government's goal to only build Zero Carbon Homes from 2016. To qualify as a Zero Carbon Home, the annual net CO_2 emissions from a dwelling in use, including all operational energy must be less than or equal to zero. This is achieved through improving energy efficiency and through renewable energy generation on site. However, the dwelling is not energy autarkic as renewable energy is exported to the grid when generated in excess of demand, and grid electricity can be imported back when needed.

Although CO_2 emissions associated with the construction of buildings are significant and can vary greatly with the types of materials and construction method used, these are not currently regulated. The impact of material use, however, is considered as part of labelling schemes such as BREEAM and the Code for Sustainable Homes.

2.4 The current Gap between Building Design and Building Performance in Housing

Good design in line with or even beyond current Building Regulations Part L can be the first step to reducing the energy demand for heating dramatically, and to avoid overheating in summer without comfort cooling. Unfortunately the design is only part of the solution. The building's performance is also very dependent on the quality of construction.

A report published by the National Trust suggests that heat loss and air-tightness concern could undermine the Government's target of achieving Zero Carbon Homes by 2016. It further states that the 'volume house building industry will struggle to meet enhanced energy performance standards for reasons that are deeply embedded in the culture, processes and practice at all levels in the industry'. This conclusion is based on research carried out at the Stamford Brook development (Lovell 2008). It identifies one of the main problems as the gap between designed performance and as-built performance. A stricter enforcement of Part L of the Building Regulations could be one solution. This would force the builders that have a "we have always done it this way" mentality to apply more appropriate construction techniques and materials, improve the skills of their personnel on and off site, and provide better their quality control.

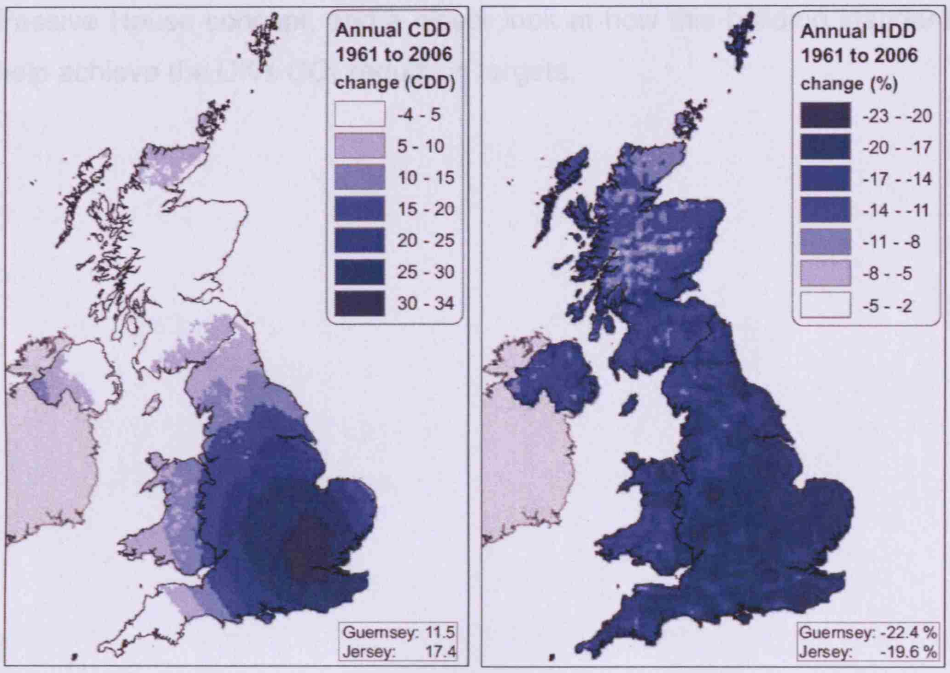


Figure 3 Percentage change in annual cooling degree days (CDD, left) and heating degree days (HDD, right) from 1961 to 2006 based on a linear trend (Jenkins 2007)

But even the tools used for design need to be reviewed. The Standard Assessment Procedure (SAP) used to regulate the energy performance of domestic buildings in the UK (DEFRA, BRE, & ODPM 2008) is based on 1970s and 1980s data and thus is not fit for purpose to predict the thermal performance of low-energy dwellings (Reason 2008). Furthermore, increased cooling demand (Figure 3) needs to be given more attention during design. Although the 2005 version of SAP includes an algorithm to assess the impact of thermal mass on overheating risk in the summer, it does not include for the effects of thermal mass on heating demand.

An alternative approach that has been tried and tested in other Northern European countries is the Passive House standard developed in Germany. It addresses the issue of accidental heat losses and heat gains by imposing rigorous design and performance standards, aimed to reduce space heating demand and, to a lesser degree, cooling demand. It also defines a limit for the total primary operational energy consumption. Following is an introduction to the Passive House concept, and a closer look at how this building standard could help achieve the UK's CO_2 reduction targets.

3 Passive House Design

3.1 Definition

The term "Passive House" (from the German word "Passivhaus") describes a particular type of energy-efficient construction standard for buildings with good comfort conditions during winter and summer, without the need for a traditional heating system.

The first Passive House was built in 1990 in Darmstadt, Germany. In 1996, Dr. Wolfgang Feist founded the Passivhaus Institut (PHI) in Darmstadt as an independent research facility. Besides their basic research on energy-efficient buildings, PHI promotes and controls the Passive House standard. Today, more than 8,000 buildings have been built to Passive House standard in Germany, Switzerland and Austria, but also in Mediterranean climates such as Spain and Italy.

A building qualifies as a Passive House when it fulfils the following criteria set by PHI (Feist 2006):

- Heating demand $\leq$ 15kWh/(m^2a) (Central Europe);
- Heating load $\leq$ 10W/m^2;
- Air tightness n50 $\leq$ 0,6/h;
- Primary energy consumption $\leq$ 120 kWh/(m^2a).

The above criteria are primarily achieved by using a highly insulated, airtight building envelope with a minimum of thermal bridging. This way it is possible to heat the building passively, which means that heat emitted by appliances or even the occupants themselves can be used to heat the building. In addition, the main glazing areas are oriented to the South to make use of passive solar gains.

Measurements in Passive Houses have shown that a minimum useful heat load of 1.0 W/m^2 can be assumed (Feist 2006). Energy efficient appliances and renewable energy sources are implemented to keep the primary energy consumption low. Figure 4 illustrates how a Passive House compliant dwelling would compare with a Building Regulations, Part L compliant dwelling (ODPM 2006).

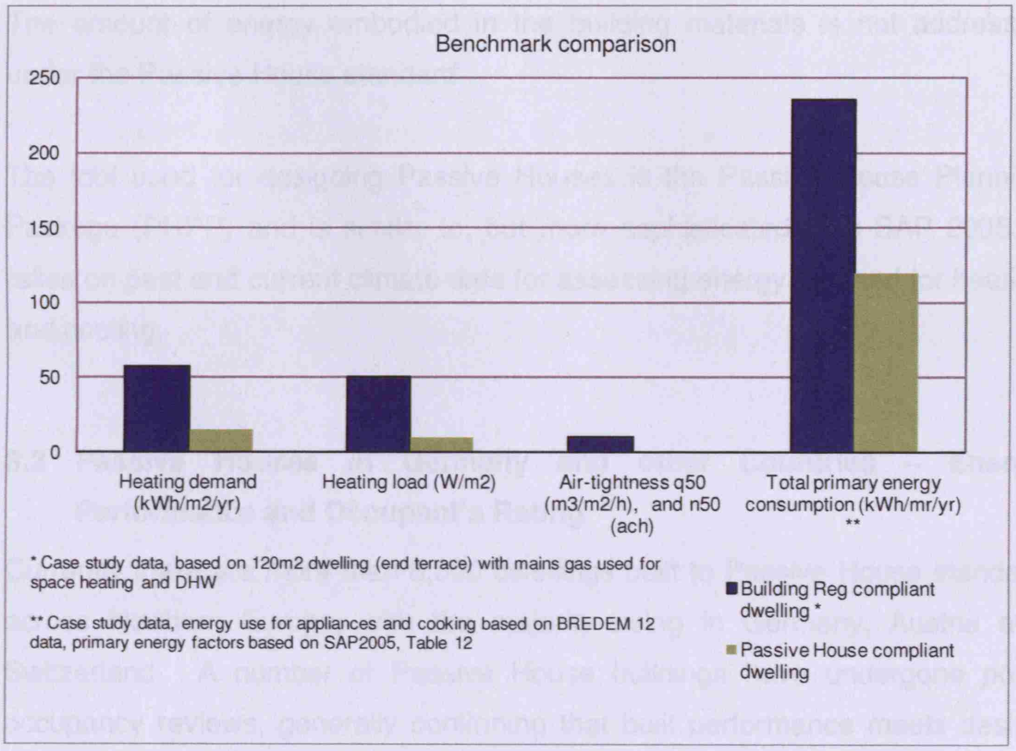


Figure 4 Comparison of Building Regulations, Part L compliant Dwelling with Passive House compliant Dwelling

It is common to use the mechanical ventilation system for supplementary space heating, as well, which then typically includes heat recovery from exhaust air to keep the energy consumption low. A minimum efficiency of 75% for heat recovery is recommended (Feist 2006), although higher efficiencies are easily achieved with products available today. A so-called "Wärmepumpenkompaktgerät" is typically employed to provide space heating, ventilation and domestic hot water heating in one unit. It consists of a mechanical ventilation system with heat recovery that includes an air-source heat pump for preheating of fresh air intake and for providing hot water. A reverse-cycle heat pump is used when in addition to heating, comfort cooling is to be provided.

The limit defined for primary energy use covers all operational energy, including space heating, comfort cooling, hot water, lighting, equipment and appliances. It thus encourages the use of energy-efficient lighting and household appliances. The amount of energy embodied in the building materials is not addressed under the Passive House standard.

The tool used for designing Passive Houses is the Passive House Planning Package (PHPP) and is similar to, but more sophisticated than SAP 2005. It relies on past and current climate data for assessing energy demand for heating and cooling.

3.2 Passive Houses in Germany and other Countries – Energy Performance and Occupant's Rating

Currently there are more than 8,000 dwellings built to Passive House standard across Northern Europe, with the majority being in Germany, Austria and Switzerland. A number of Passive House buildings have undergone post-occupancy reviews, generally confirming that built performance meets design performance. In many cases it was observed that Passive House dwellings with high thermal mass contained within the insulated building envelope usually produce higher energy use in the first year(s) of occupancy. It appears that a significant percentage of heating demand during that period goes to 'preheat' the thermal mass elements to internal comfort temperatures. This also creates problems for dwellings that are only occasionally occupied, as the heating system has a limited capacity and might not be able to provide comfort temperatures immediately.

Occupant surveys carried out for Passive House developments in various countries show that high satisfaction levels and thermal comfort levels are achieved (see 5.2). This is not only beneficial to the occupant's health and well-being. It also limits the likelihood for occupants using excessive amounts of energy for heating and cooling.

3.3 How can Passive Houses help fulfil the UK Goals?

Figure 4 shows a typical Building Regulations, Part L compliant dwelling in comparison with a Passive House compliant dwelling, indicating the large potential for improvement.

It is estimated that in 2006 there were 25.6 million dwellings in the UK, with a total energy consumption from space heating, hot water use, lighting and appliances use of 45.7 million toe (BERR 2008a), the equivalent of 713 million MWh primary energy. In 1996 the average dwelling size in England was estimated to be $85m^2$ (National Statistics 1997). Assuming that the average size still applied today, the average energy consumption in 2006 can be estimated as $244kWh/m^2/yr$. Total associated CO_2 emissions are calculated as 132 million tons per annum.

Table 2 presents a comparative study of the UK's housing stock. It suggests that dwellings built to Passive House standard would reduce heating demand by almost 90% compared to 2006 building stock, and cut out two-thirds of the CO_2 emissions. The conclusion can be drawn that if all housing in the UK was refurbished to Passive House standard, the targeted 60% CO_2 emission reduction by 2050 compared to 1990 levels could already be achieved in the housing sector today. This is, however, if energy needed for the refurbishment is ignored. It is also important to recognise the Passive House standard can be applied to other non-domestic buildings where similar results have been achieved (Feist 2006).

Both current Building Regulations Part L and PHPP rely on past and current climate data to assess energy demand. It is therefore unclear whether the energy consumption target can still be achieved in the future, particularly considering the effects of global warming and increasing overheating risk. Passive design measures such as thermal mass might be necessary to moderate the effects of global warming on the thermal performance of buildings.

Table 2 Comparative study of UK housing stock

Comparative study	1990 housing stock ^	2006 housing stock ^	Part L compliant dwelling *	Passive House **
No. of dwellings ^ (million)	22.6	25.6		
Total delived energy ^ (million toe)	40.8	45.7		
Space heating demand (kWh/m2/yr)	143	141	39	15
Hot water demand (kWh/m2/yr)	61	61	39	21
Appliances and other (kWh/m2/yr)	42	42	52	47
Total, delivered (kWh/m2/yr)	246	244	130	84
Total, primary (kWh/m2/yr) +	352	350	235	120
Total (million MWh)	678	713	480	245
Total associated CO2 emissions (million tons CO2/yr) ++	119	132	89	45
Reduction in space heating demand per m2 (%)	**baseline**	**1%**	**73%**	**89%**
Overall reduction in CO2 emissions (%) over 1990 stock	**baseline**	**-10%**	**26%**	**62%**

* based on Target Emissions Rate (TER) for 70m2 dwelling from SAP 2005 (DEFRA, BRE and ODPM, 2008)

** based on benchmarks per Passive House definition, and SAP results

\+ based on primary energy factors 1.15 for mains gas, and 2.8 for grid electricity

++ based on BERR data for fuel mix (BERR, 2008), and SAP 2005 carbon intensities for fuel types (DEFRA, BRE and ODPM, 2008)

^ based on BERR data for energy consumption in the UK (BERR, 2008)

Neither SAP 2005 nor the (PHPP) are considering embodied energy and CO_2. As Passive Houses and other low-energy dwellings achieve very low operational energy demand, the ratio of embodied energy to operational energy increases.

Bearing in mind the above, the following questions arise:

1. How will Passive Houses perform over their lifetime considering global warming?
2. To what degree can passive design measures be used to limit the negative effects of global warming on the thermal performance of a Passive House?

3. Which role does embodied energy play in the selection of the passive design measures?

The methodology used to address these questions is detailed in the following chapter.

4 Aim and Scope

The purpose of this study is to assess the role that Passive Houses could play in the quest to significantly reduce CO_2 emissions by 2050 and beyond. So far, works by others have focused on the current performance of Passive Houses, and are limited to the operational energy demand. The study aims to assess both energy demand and CO_2 emissions of a sample Passive House over its lifetime including energy and CO_2 embodied in the building structure, and to determine the role that passive design measures play.

This study is based on an already built Passive House in Hannover-Kronsberg in Germany. This case study was chosen as a base model as extensive data is available in terms of design performance and built performance. Furthermore, this type of dwelling fits well in the type and size of housing provided in the UK today.

The first step of the study consists of dynamic thermal modelling of the existing building used as a base model. It is simulated in TAS and tested with Hannover weather data to validate model results. The base model is then simulated with CIBSE weather data for London, and predicted heating demand and overheating risk for this location recorded. Assumptions are made about predicted cooling demand if applicable.

The base model is also tested with predicted climate data for London based on the IPCC 'medium high risk' global warming scenarios for key years 2020, 2050 and 2080. Again, heating, overheating risk and cooling demand are estimated, based on the same temperature benchmarks and overheating criteria that are used today. Conclusions will be drawn on how the existing building would perform over its lifetime if it was built in London today (2010).

In a second step, the building is modified to investigate the impact that high thermal mass, low thermal mass and other passive design measures would have on the above recorded parameters. Each modified model scenario is tested with current CIBSE weather data, as well as with predicted weather data for 2020, 2050 and 2080.

In a third step, the difference in embodied energy is estimated for each building scenario and compared to the base model.

For each scenario, the impact that both operational energy demand and embodied energy have on overall energy use and CO_2 emissions is analysed. Conclusions are drawn to determine how to achieve the highest CO_2 emissions savings over the lifespan of the buildings.

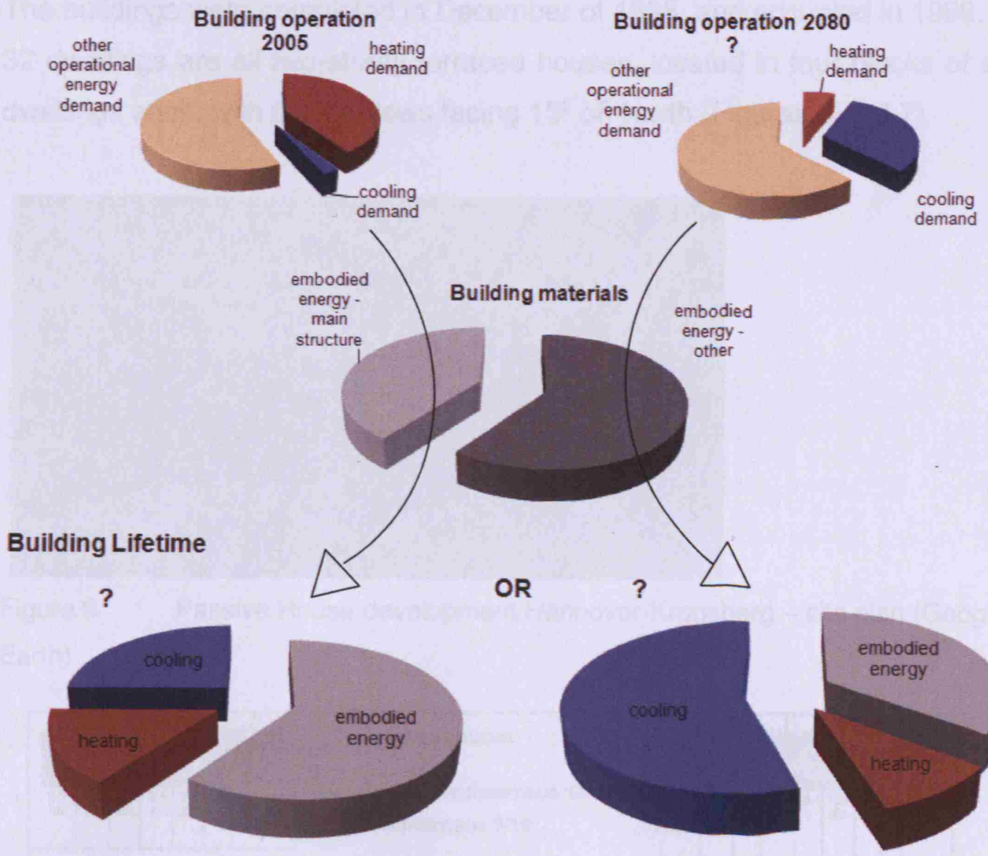


Figure 5 Study rational

5 Case study – Passive House Development in Hannover-Kronsberg, Germany

5.1 The site

The Passive House considered here is one of 32 dwellings built in the first phase of a development at 30-124 Sticksfeld in Hannover-Kronsberg in Germany (Figure 8). The development has been one of the projects featured in the “Cost-Efficient Passive House As European Standard” (CEPHEUS) research project carried out by the Passivhaus Institut in Darmstadt and others, and sponsored by the European Commission.

The buildings were completed in December of 1998, and occupied in 1999. The 32 dwellings are all two-storey terraced houses, located in four blocks of eight dwellings each, with the windows facing 15º off North (Figures 6 and 7).

Figure 6 Passive House development Hannover-Kronsberg – site plan (Google Earth)

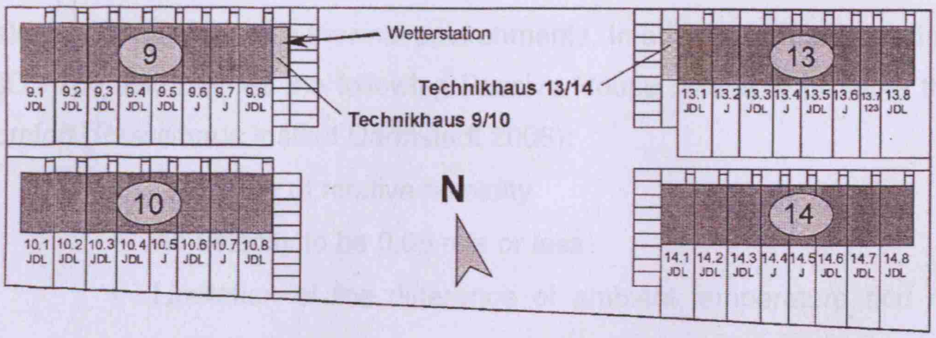


Figure 7 Passive House development Hannover-Kronsberg – site plan

5.2 Thermal Performance

The thermal performance of buildings is often measured in terms of thermal comfort. A common definition of thermal comfort is "the condition of mind which expresses satisfaction with the thermal environment" (Parsons 2003). The method that is most widely used to define the level of thermal comfort was developed by P.O. Fanger in 1970. Fanger suggested that the degree of thermal discomfort depends on the thermal load, as well as the activity level a person is exposed to. He developed an equation for the predicted mean vote (PMV), with a 7-point comfort scale from +3 (hot) to –3 (cold).

The PMV takes into account the following steady-state thermal balance factors (Parsons 2003):

- Air temperature
- Mean radiant temperature
- Air velocity
- Relative humidity
- Activity level
- Clothing level

While the first four factors set out by Fanger are driven by the thermal performance of the building, activity level and clothing level are variables individually controlled by each occupant. However, this report will focus on the thermal performance of the building.

Fanger's method was adopted in ISO 7730:1994 for the thermal comfort calculations of moderate thermal environments. In addition to Fanger's findings, ISO 7730 also defines the following Passive House criteria to promote thermal comfort (Passivhaus Institut Darmstadt 2006):

- Limitation of relative humidity
- Air velocity to be 0,08 m/s or less
- Limitation of the difference of ambient temperature and radiant temperature
- Limitation of asymmetric radiant temperature to 5°C or less

- Limitation of vertical temperature differences of 2°C or less
- Limitation of temperature differences within a room of 0.8°C or less

Figure 8 Passive House development Hannover-Kronsberg

As part of the CEPHEUS research project, the thermal performance of Passive Houses in Hannover-Kronsberg, Germany were measured in situ (Feist, Peper, & Goerg 2001):

The test results can be summarised as follows:

- mean room temperature of 21.1°C with a range of 20.9 –25.7°C;
- 2.5% of hours of year above 25°C;
- mean relative humidity of 38% with a range of 26-49%;
- mean air-tightness of 0.29 ach with a range of 0,17-0,4 ach.

The air velocity and mean radiant temperature were not measured. However, testing of similar Passive Houses in Lucerne, Switzerland showed that the air velocity stays below 0,025 m/s (Feist, Peper, & Goerg 2001). The radiant temperatures were found to be a maximum of 1°C below that of the air temperature.

When the above values are used to determine the thermal comfort level based on Fanger's model, the following can be found:

- mean value (sitting), PMV = -0.7 (PPD = 15.3%);
- mean value (light activity), PMV = -0.6 (PPD = 12.5%);
- low value (winter), PMV = -0.9 (PPD = 22.1%);
- high value (summer), PMV = -0.1 (PPD = 5.2%).

As all the PMV values calculated are negative, the Passive Houses tested appear to be slightly cold according to Fanger's theory. The calculation results can be found elsewhere (Borchers 2007).

5.3 Occupant Questionnaire

An occupants survey was carried out at the development in the years 2000 and 2001, and consisted of personal interviews and written questionnaires (Feist, Peper, & Goerg 2001) of both home owners and tenants. Some of the results from the Hannover-Kronsberg survey in 2001 are listed below:

- Overall User Satisfaction: 97%
- Satisfaction with Winter Indoor Climate: 100%
- Satisfaction with Summer Indoor Climate: 88%
- Satisfaction with Air Quality: 95%
- Satisfaction with Ventilation System: 96%

The percentage of unsatisfied occupants "overall" averages 3%. Therefore the survey results are better than those determined with Fanger's model. Particularly the slightly cold conditions are not confirmed. However, both model and survey cannot be compared one-to-one, as the survey measured the fulfilment of expectations rather than the dissatisfaction level. This may also include other factors such as energy cost and handling of the house technology.

Overall it can be concluded that based on the survey the subjective comfort level is very high. Occupants who participated in the survey seem to mainly be unsatisfied with increased temperatures in the summer time. The personal interviews also showed that occupants particularly valued the relatively small temperature differences within the room, and between the surface temperatures and ambient temperatures. Another interesting finding in the CEPHEUS survey was that 82% of the occupants rely entirely on the ventilation system to exchange air within the building. Only 18% of the occupants opened windows for short or longer periods.

5.4 Energy use and CO_2 emissions

Energy use was recorded for 22 permanently occupied dwellings from 1 October 1999 to 30 September 2000 (Peper, Feist, & Kah 2001).
The results can be summarised as follows:

- Space heating demand (delivered) 16 kWh/m^2/yr
- Maximum heating load (averaged over one day) 8.8 W/m^2/yr
- Electricity (delivered) 23.3 kWh/m^2/yr
- Domestic hot water demand (delivered) 13.7 kWh/m^2/yr
- Total primary energy demand 82.6 kWh/m^2/yr

The results suggest that although the space heating demand does slightly exceed the limit of 15 kWh/m^2/yr defined by the Passivhaus Institut, the overall primary energy demand stays well below the benchmark of 120 kWh/m^2/yr. In fact, the primary energy consumption is less than a third of the UK's estimated primary energy consumption for 2006 (see Table 2).

Based on SAP 2005 calculation (Appendix A12), the Passive House would achieve a DER of 8.4 kgCO_2/m^2/yr. This includes solar thermal water heating and communal space heating.

The following chapter will analyse how the same Passive House would perform in terms of its thermal performance under current and future UK climatic conditions, using London as an example.

6 Thermal Modelling

6.1 Model Set-up

The sample building used for this study was taken from the Passive House development in Hannover-Kronsberg in Germany (see chapter 4). It consists of a 119m^2 two-storey end-of-terrace dwelling, primarily light-framed with concrete slabs at ground floor and upper floor. A building section and floor plans and are shown in Figures 9 and 10 respectively. This dwelling was chosen since in the past it was used as the basis for an extensive thermal modelling and post-occupancy survey as part of the CEPHEUS research project (Feist et al. 2005;Kaufmann & Feist 2001). The survey confirmed that built performance meets or even exceeds design performance.

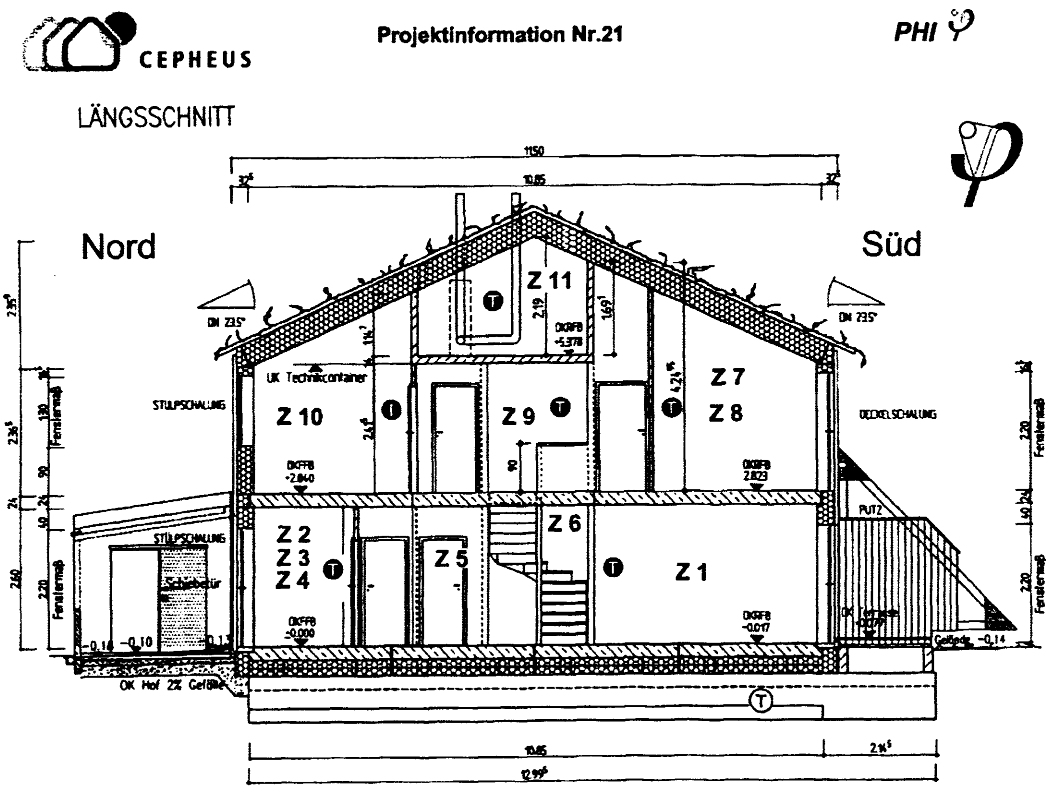


Figure 9 Building section

The software used for the thermal modelling is TAS Building Designer, which allows dynamic building simulation with integrated natural and forced airflow (EDSL 2006). Since the study carried out in Germany showed that thermal modelling results did generally match those measured in-situ in Germany, the same input data was used for the TAS model used in this study. The TAS model was then used to simulate the building's thermal performance under UK climate data. It should be noted that although the UK climate is generally milder than that in Hannover (Figure 12) that the same input would still be applicable.

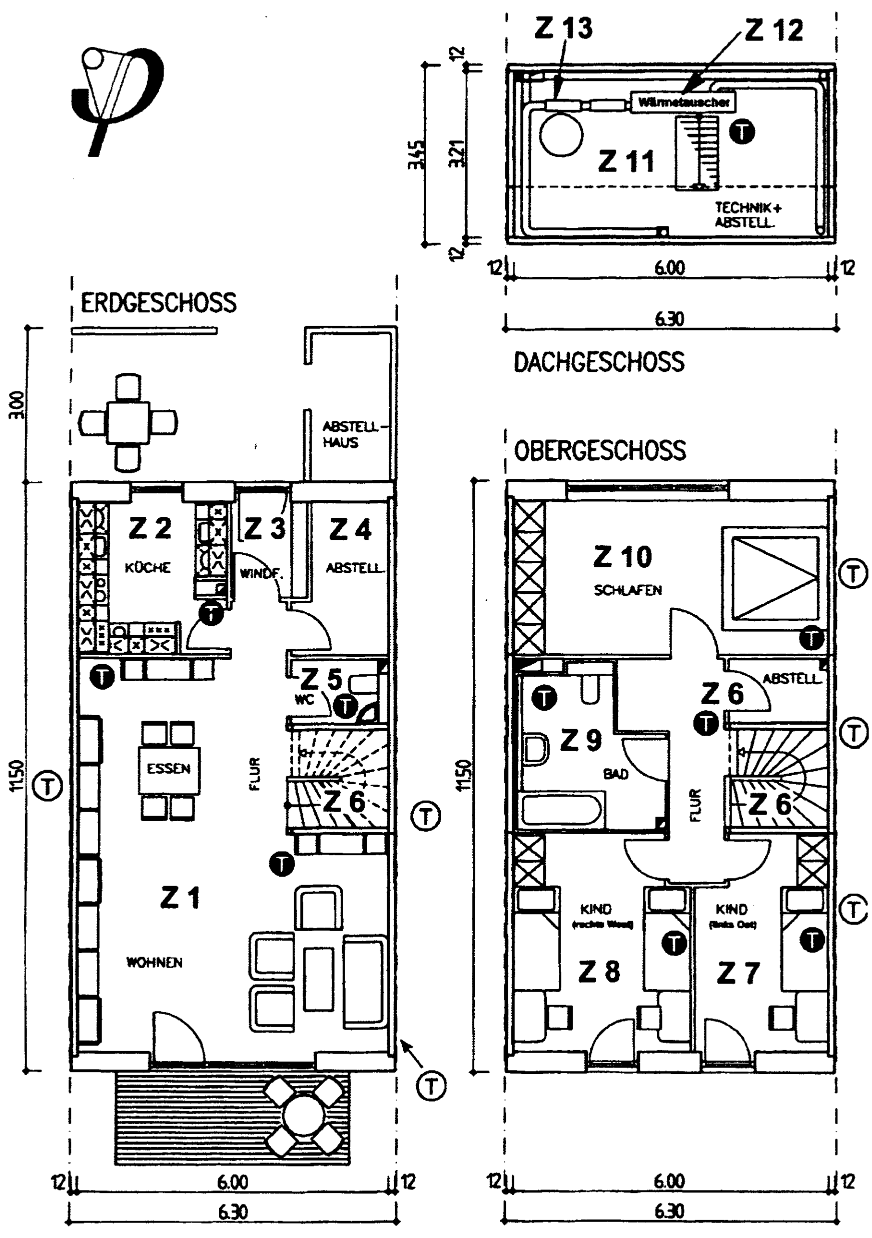


Figure 10 Building ground floor plan (left), upper floor plan (right) and service room in roof space (top right)

Input data was such as dimensions and zoning was taken from the CEPHEUS studies where available. This includes inter-zone air movement based on the

MVHR system, and air leakage through the building envelope (Table 3). Average internal heat gain loads are also taken from the CEPHEUS study. However, occupancy schedules could not be obtained. Instead, the average loads were converted to temporary loads, based on assumed typical occupancy schedule (Table 4).

Table 3 Inter-zone ventilation rates

Inter-zone air flow	**From Zone (g/s)**													
To Zone (g/s)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.34	0.00	0.34	0.00	27.00	0.00
1	0.34	0.00	121.50	121.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.40
2	0.34	121.50	0.00	121.50	0.00	0.00	3.51	0.00	0.00	0.00	0.00	0.00	0.00	5.40
3	0.34	121.50	121.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	3.51	0.00	0.00	0.00	0.00	1.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	1.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.34	0.34	0.34	0.00	0.00	0.00	125.01	125.01	121.50	130.41	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	121.84	0.00	0.00	0.00	0.00	0.00	0.00	3.51
8	0.00	0.00	0.00	0.00	0.00	0.00	121.84	0.00	0.00	0.00	0.00	0.00	0.00	3.51
9	0.00	0.00	0.00	0.00	0.00	0.00	132.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	121.84	0.00	0.00	0.00	0.00	0.00	0.00	8.91
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	27.00	0.00	8.91	0.00	5.40	1.89	0.00	0.00	0.00	10.80	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	27.00	0.00
	Based on CEPHEUS Report 21, tables 5 and 6, m3/h converted in g/s (air density of 1.2kg/m3, 20?C, 101 Pa)													

Heat recovery from exhaust air to fresh air intake is modelled by drawing exhaust air and fresh air intake through the service room, Zone 13. The neighbouring dwelling is modelled as being at a constant temperature of 19ºC. Both are assumed to have an effect on calculated heating and cooling demand. However, due to lack of information these two parameters could not be modelled accurately within this analysis.

Apertures are modelled as being continuously shut when the dwelling is comfort-cooled or heated. For the overheating check without comfort-cooling, night-purging is used. Apertures are modelled such that from 20:00 to 8:00 they start opening when the resultant temperatures in the relevant room reaches 24ºC, and are fully opened at 28ºC. In addition, the kitchen window opens during assumed cooking times as the related temporary heat gains would lead to disproportional overheating. In the Passive Houses in Hannover this is controlled by running an exhaust fan for the kitchen only.

The temperature criteria is based on CIBSE Guide A benchmarks for dwellings (Humphreys, Nicol, & et al 2006), and is defined as shown in Table 5. It should be noted that the occupied hours considered for checking overheating risk in the bedrooms is 22:00 to 8:00. For the living room the relevant occupied time is 8:00 to 22:00.

Table 4 Internal heat gain schedule

Heat gain schedule - week days	Hours						
Room	0-4	4-8	8-12	12-16	16-20	20-24	Gain (W/m2) **
							4
							1
Living room *							0.67
							10
							1
Bedrooms *							0.67
							1
Kitchen							0.67/67
							10
							1
Bathroom							0.67
							1
Other rooms							0.67
Service room							5

Heat gain schedule - weekend	Hours						
Room	0-4	4-8	8-12	12-16	16-20	20-24	Gain (W/m2) **
							4
							1
Living room *							0.67
							10
							1
Bedrooms *							0.67

* Schedule varies between weekday and weekend

** Based on values from CEPHEUS report 21, Tables 2, 3 and 4, schedule assumed

- occupancy gains
- lighting gains
- equipment gains (appliances etc.)

6.2 TAS modelling for Hannover climate

Historic Test Reference year (TRY) weather data from 1979 for Hannover, Germany was used, as provided by TAS to test the TAS model against measured results. Temperatures are used as measured and simulated within the CEPHEUS study.

The TAS model produces an estimated heating demand of 11.2 kWh/m^2/yr. This is in line with a predicted heating demand of 11.8 kWh/m^2/yr as calculated with the Passive House Planning Package (PHPP), and with the 13.3 kWh/m^2/yr measured in-situ as part of the CEPHEUS studies. It is assumed that differences occur mainly due to a difference in required temperatures within the various spaces. PHPP assumes a required internal temperature of 20ºC in all rooms, while CIBSE temperature benchmarks (Table 5) were used for the TAS model. A likely main cause for the difference of measured results and modelled results is the TAS weather data not being identical with the climate recorded during measurement.

Table 5 Benchmark temperatures

Comfort temperatures (CIBSE Guide A, Tables 1.5, 1.7 and 1.8)	Winter operative temperature (ºC)	Summer operative temperature, comfort cooling (ºC)	Operative temperature for indoor climate, no comfort cooling (ºC)	Benchmark summer peak temerature, no comfort cooling (ºC)	Overheating criteria, no comfort cooling	Comment
Dwelling, living room	22-23	23-25	25	28	1% of annual occupied time above 28ºC	Highest value in range is used
Dwelling, bedroom	17-19	23-25	23	26	1% of annual occupied time above 26ºC	Highest value in range is used
Dwelling, kitchen	17-19	21-23	n/a	n/a	n/a	Highest value in range is used
Dwelling, bathroom	20-22	23-25	n/a	n/a	n/a	Highest value in range is used
Dwelling, hall/stairs/landing	19-24	21-25	n/a	n/a	n/a	No heating/cooling of these spaces
Dwelling, toilet	19-21	21-23	n/a	n/a	n/a	Highest value in range is used

In the CEPHEUS study, the overheating criteria was assumed as the time that internal temperatures exceed 25ºC. This was recoded as 2.5% of the time. The average daily temperature on the hottest day of the year was recorded as 25.7ºC. This is lower than the TAS results that predict 6% of time when indoor temperatures exceed 25ºC. However, the differences could be explained with the variation in climate data, as well as the use of internal shading that is not considered in the TAS model.

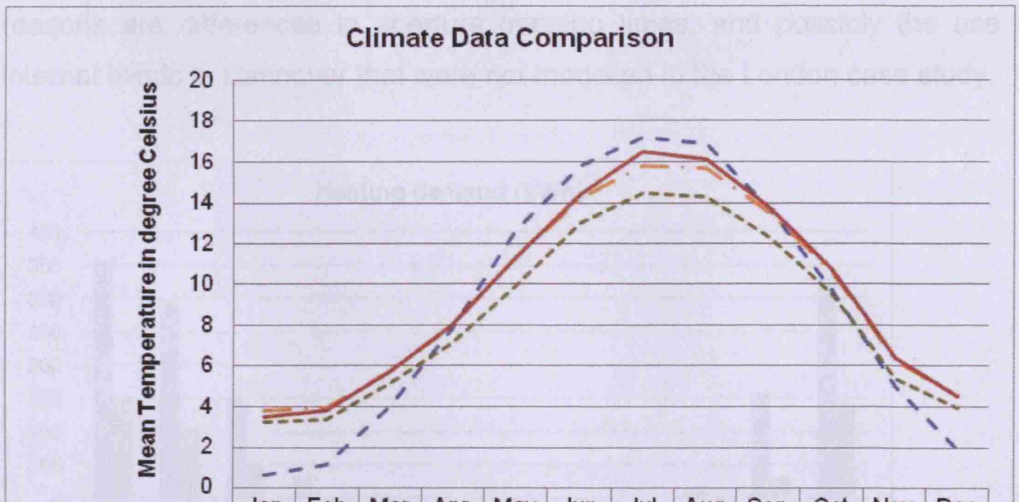
Overall, it is concluded that the TAS modelling results are accurate enough to predict heating demand. It is further assumed that the model will predict overheating potential and cooling demand to a satisfactory accuracy. The model is therefore used for this study.

6.3 TAS modelling for UK climate today

Climatic conditions vary across the UK depending on geographic location, topography and local land use. CIBSE historic weather data for London Heathrow is used for this analysis, representing typical climate parameters as measured over the period from 1983 to 2005. It incorporates a heat island effect of about 5K due to its proximity to the airport, therefore having similar properties to that of central London with an estimated heat island effect of 6K (Humphreys, Nicol, & et al 2006). The modelling results will thus be representative for the majority of urban environments in the Southeast of the UK.

The base model for the Passive House at Hannover-Kronberg is used here. Besides the use of different climate data, all other input data remains the same as for the Hannover model.

CIBSE have produced hourly weather data based on Met Office data during the period 1983-2004. These weather data are typically used for thermal modelling in order to assess thermal conditions in the built environment and could be seen as representative of UK climate in the 1990s. In line with current standard practice, a CIBSE Test Reference Year (TRY) weather file is used for determining the heating demand, whereas CIBSE Design Summer Year (DSY) weather file is used to calculate the overheating risk and to estimate cooling demand in the summer months.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hannover	0.6	1.1	4	7.8	12.6	15.8	17.2	16.9	13.7	9.7	5	1.9
Manchester	3.8	3.9	5.7	7.9	11.3	14.2	15.8	15.7	13.5	10.6	6.3	4.5
Edinburg	3.2	3.3	5.1	7.1	9.9	13	14.5	14.3	12.3	9.5	5.4	3.9
London	3.5	3.8	5.7	8	11.3	14.4	16.5	16.1	13.8	10.7	6.4	4.5

Figure 11 Climate Comparison

The results for the London base model show that the estimated annual heating demand of 4 kWh/m^2 is substantially lower than the 11.2 kWh/m^2 calculated for the Hannover model (Figure 13). This is explained with the climatic differences between Hannover and London, the main factor being warmer winters in London (Figure 12). The milder winters in London lead to a 15% HDD decrease, subsequently resulting in a 64% decrease in heating demand. The change in heating degree days is not proportional to the change in active heating demand as 76% of the total heating demand is supplied with beneficial heat gains such as lighting, appliances and occupants. This demonstrates very well to what high degree Passive Houses are able to utilise internal heat gains.

The results reveal that the bedrooms generally do not tend to overheat during occupied hours while the living room does see prolonged times with temperatures above 28ºC in June and July (Figure 14). Although due to the more temperate climate in London overheating was expected to be less of an issue compared with Hannover, this is not confirmed with the results. While in Hannover, temperatures in excess of 25ºC were recorded only 2.5% of the time, the time increases to 20% for the London case. It is assumed here that the main reasons are differences in aperture opening times, and possibly the use of internal blinds in Hannover that were not modelled in the London case study.

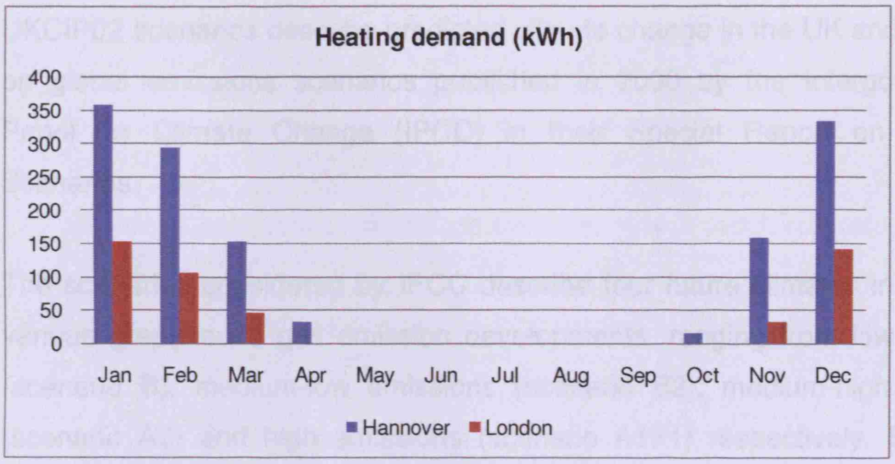


Figure 12 Result comparison, Hannover and London

Based on the results it is expected that due the future climate change, heating demand will decrease and that comfort cooling will have to be introduced due to an increase in overheating times. The future change over time in heating demand, overheating occurrence and cooling demand where applicable is investigated next.

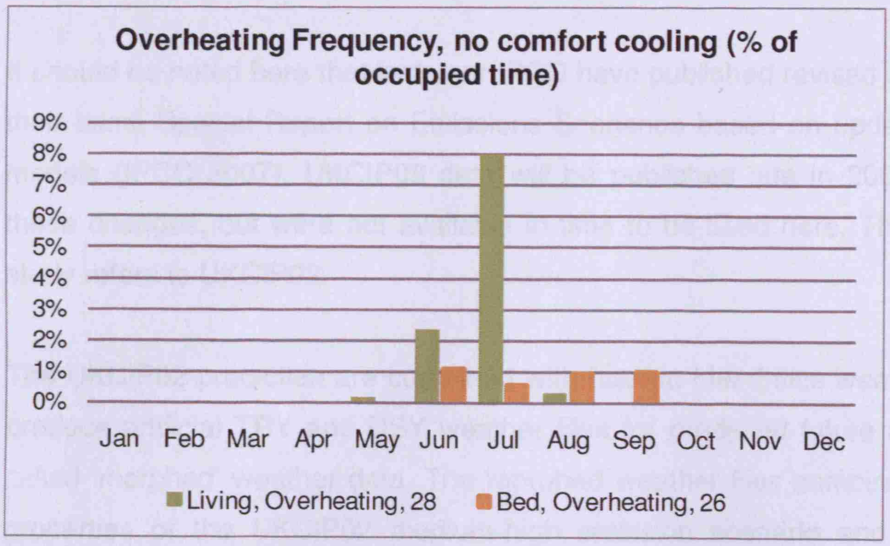


Figure 13 Overheating risk – base case

6.4 TAS modelling for future UK climate

UKCIP02 climate scenarios are used to analyse the thermal performance of the Passive House base model under future predicted climatic conditions. The UKCIP02 scenarios describe predicted climate change in the UK and are based on global emissions scenarios published in 2000 by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios.

The scenarios considered by IPCC describe four future climates in relation to various greenhouse gas emission developments, ranging from low emissions (scenario B), medium-low emissions (scenario B2), medium-high emissions (scenario A2) and high emissions (scenario A1F1) respectively. Scenario B predicts a mean global temperature rise of 2ºC by the 2080's compared with 1961-1990 average data, with the atmospheric CO_2 concentration reaching 525ppm. In contrast, high emissions scenario A1F1 predicts a temperature increase of 3.9ºC over the same period, with the atmospheric CO_2 concentration rising to as much as 810 ppm. In order to limit the amount of data, only one of the four emission scenarios is used here; namely the medium-high scenario A2 with a mean global temperature rise of 3.3ºC by the 2080's and an atmospheric CO_2 concentration reaching 715 ppm.

It should be noted here that last year IPCC have published revised scenarios in their latest Special Report on Emissions Scenarios based on updated climate models (IPCC 2007). UKCIP08 data will be published late in 2008 to reflect these changes, but were not available in time to be used here. Therefore this study refers to UKCIP02.

The UKCIP02 prediction are combined with historic Met Office weather data to produce artificial TRY and DSY weather files for predicted future climate, so-called 'morphed' weather data. The morphed weather files combine the mean properties of the UKCIP02 medium-high emission scenario and the hourly variation of the original TRY and DSY files. The methodology is based on works by others (Belcher, Hacker, & Powell 2005). Weather files are generated for key years 2020, 2050 and 2080. These weather files are used in TAS to predict heating demand, overheating risk and cooling demand where applicable for the key years.

The TAS simulations use the same temperature benchmarks and overheating criteria that are used today. Due to human adaptation to changing climate over time, it is likely that the upper temperature limit used for the overheating criteria can be increased in the future. As this is not considered here, times of overheating and cooling demand are likely to be an overestimation, particularly for the 2050 and 2080 predictions.

6.5 Modelling Results for the Base Model

TAS dynamic thermal modelling was used to calculate heating demand, overheating risk and cooling demand under future predicted climatic conditions.

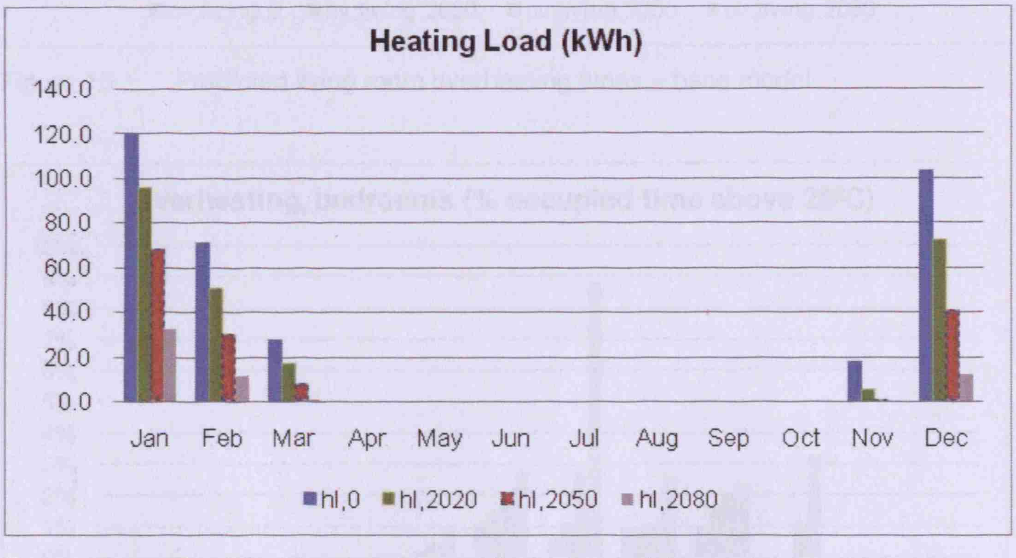


Figure 14 Predicted heating demand for base model

The results show a low heating demand under today's climate of 480 kWh/yr that decreases towards 2080. The heating period occurs from November to March (Figure 14). Results also indicate overheating risk in the living rooms for today's climate during June and July. The overheating risk increases towards 2080 with average 20% of time overheated (above 28ºC) from June to August

(Figure 15). The bedrooms do not experience excessive overheating until after 2050 with the maximum occupied time with temperatures above 26ºC being 1.6% in 2080 (Figure 16 and Table 10). Thus it can be concluded that overheating will become a problem in the future for the Passive House under consideration.

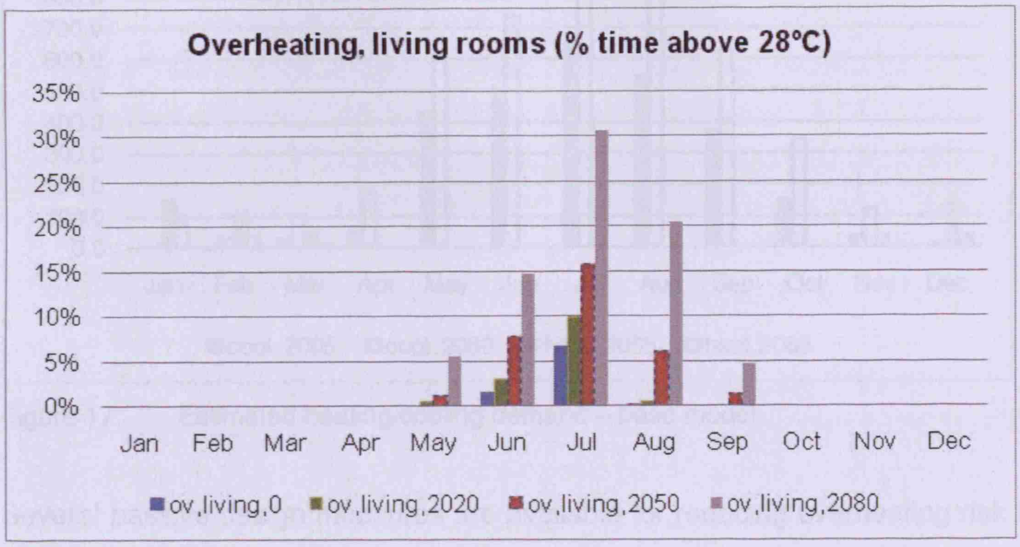


Figure 15 Predicted living room overheating times – base model

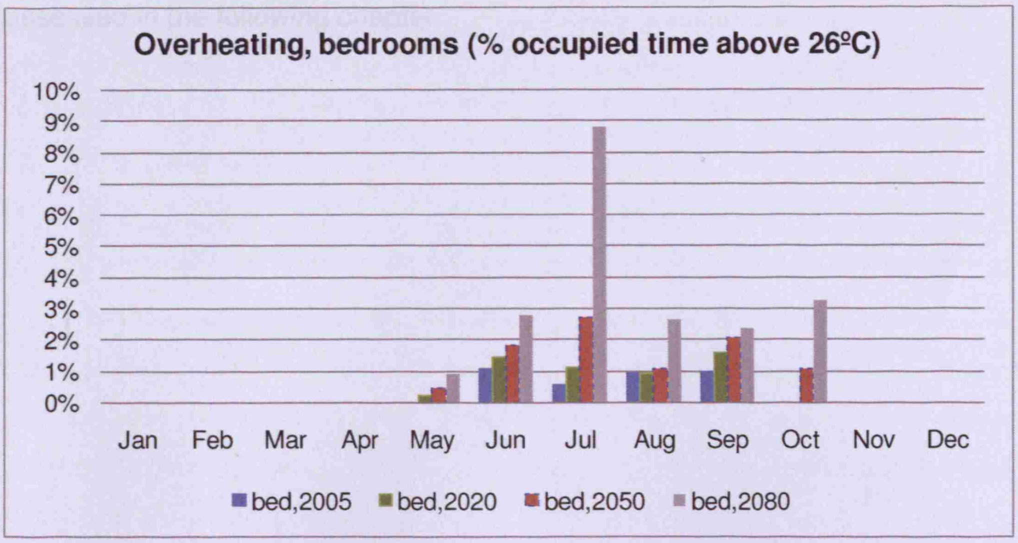


Figure 16 Predicted bedroom overheating times – base model

If the dwelling was comfort cooled, it becomes clear that heating plays a minor role in the overall energy use from the start (Figure 17) with the ratio of annual cooling demand to annual heating demand ranging from about 6 for today's climate to about 30 for 2080.

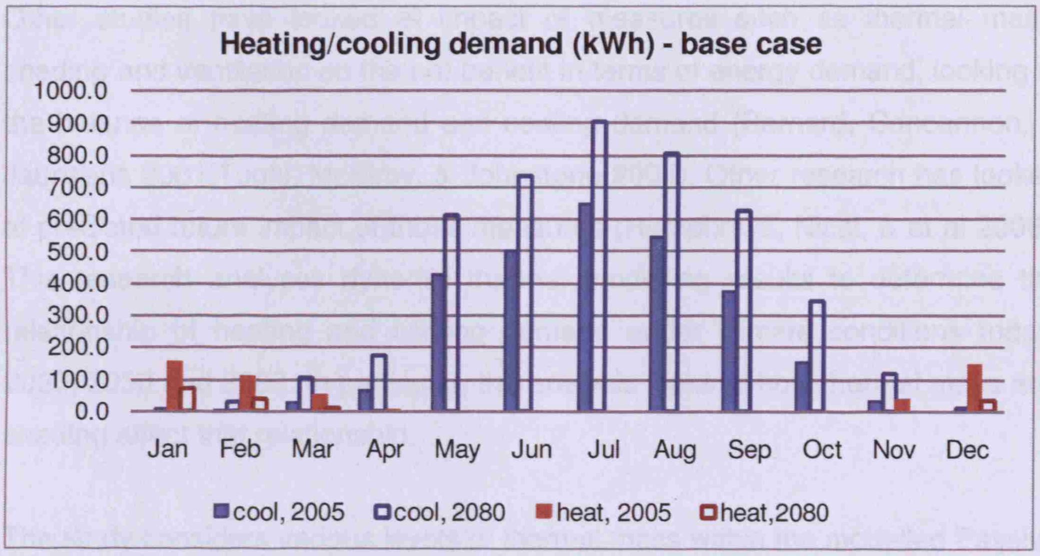


Figure 17 Estimated heating/cooling demand – base model

Several passive design measures are available for reducing overheating risk in the summer months, most of which will also have an impact on heating demand. The impact of measures such as thermal mass and shading are assessed in the following chapter.

7 Sensitivity Study

7.1 Scope

Other studies have looked at impact of measures such as thermal mass, shading and ventilation on the net benefit in terms of energy demand, looking at the balance of heating demand and cooling demand (Barnard, Concannon, & Jaunzens 2001;Tuohi, McElroy, & Johnstone 2004). Other research has looked at predicted future impact of those measures (Humphreys, Nicol, & et al 2006). This research analyses dynamic thermal modelling results to determine the relationship of heating and cooling demand under climate conditions today, 2020, 2050 and 2080. In particular, the analysis looks at how thermal mass and shading affect that relationship.

The study considers various levels of thermal mass within the modelled Passive House, as well as the use of 'indirect thermal mass' by utilising the relative constant temperature of the ground to pre-heat or pre-cool incoming air. In addition it is estimated how effective shading is compared to the thermal mass options. Besides varying the thermal mass properties, introducing pre-heating and pre-cooling of incoming air and adding shading, all other design parameter are kept constant, including U-values of all building elements.

7.2 Thermal Mass

In general, thermal mass is a material that has the capacity to store heat. It is measured in terms of 'Volumetric heat capacity', the quantity of heat per unit mass per degree of temperature change or kJ/m3K. When designed and built appropriately, thermal mass can be utilised to moderate fluctuations in space temperature in buildings and therefore contribute to maintaining thermal comfort. It can therefore also significantly reduce the requirement for active heating and cooling systems. Materials suitable for thermal mass application in buildings typically have high heat capacity, moderate conductance, moderate density and high emissivity.

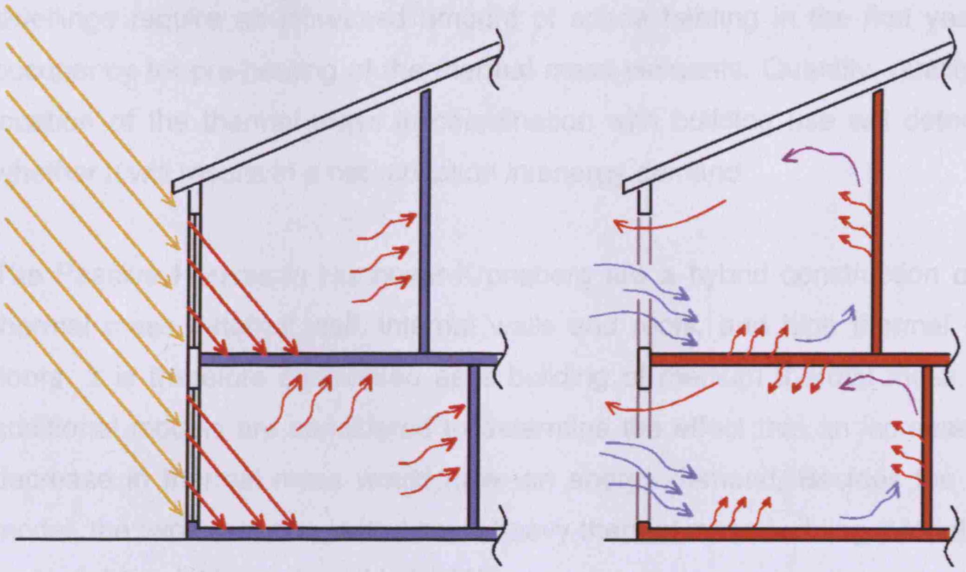


Figure 18 Thermal mass effect - schematics

The historic use of thermal mass in buildings has been well established to counteract overheating in hot arid climates where diurnal temperatures allow heat to be stored during the day, and released during the night. In cold temperate climate, heat loss during winter is currently of greater concern than overheating in summer. Therefore, in counties such as the UK, buildings must be insulated from heat loss, while exposing thermal mass to the inside. In dwellings, thermal mass is ideally exposed to winter sunlight to allow beneficial solar gains to be stored. Non-domestic buildings, however, suffer from extensive internal heat gains throughout the year. In this case, thermal mass would be used to temporarily store unwanted heat during occupied hours, and to release in at other times. Besides factors mentioned above, the effectiveness of thermal mass depends on the ratio of exposed surface area to thickness.

The material most commonly used for thermal mass in the UK is concrete and other forms of masonry. In housing it can be utilised to temperate the building in the summer, and to temporarily store beneficial solar gains in the winter. However, increased thermal mass can result in increased heating demand in winter months (Barnard, Concannon, & Jauzens 2001). Measurements in several existing Passive Houses with high thermal mass reveal that these dwellings require an increased amount of space heating in the first years of occupancy for pre-heating of the thermal mass elements. Quantity, quality and location of the thermal mass in coordination with building use will determine whether it will results in a net reduction in energy demand.

The Passive Houses in Hannover-Kronsberg are a hybrid construction of low thermal mass external wall, internal walls and roofs, and high thermal mass floors. It is therefore considered as a building of medium thermal mass. Two additional models are considered to determine the effect that an increase and decrease in thermal mass would have on energy demand. Besides the base model, the two scenarios tested are a heavy thermal mass building (Model HW) and a light-weight structure (Model LW).

The **Passive House base case** is primarily a timber light-framed building with concrete ground floor and upper floor. Tiles are used for floor finishes, while the underside of slabs and the wall finish consists of plasterboard and plaster.

Model LW consists of timber-framed elements for external walls, internal walls floors and roof. To control heat loss all structural timber elements are insulated in-between structural members such as studs and joists, and in addition are heavily insulated on the outside face. Overall, U-values of elements are kept the same as the base case and all other parameter are identical.

Model HW consists of exposed concrete elements for external walls, internal walls and floors. To control heat loss, both external walls and ground floor are heavily insulated on the outside face. Overall, All other parameters are identical with the base case. It is recognised here that the thermal mass element will cause increased heating demand during the first years due to preheating pre-heating. A 365 day preheating period was used in this instance as this is the maximum allowed in TAS. The author acknowledges that the period might not be sufficient to preheat all thermal mass and TAS might therefore overestimate heating demand.

7.3 Ground-coupled heat exchanger

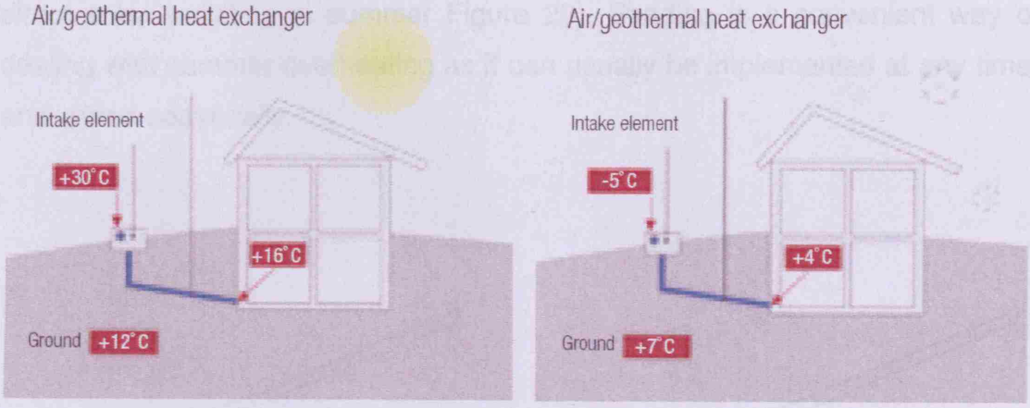
Ground-coupled heat exchanger, also known as earth-to-air heat exchangers (EAHX) utilize the earth's relative constant temperature to warm or cool incoming fresh air. As such they can be seen as 'external thermal mass'. If space and soil conditions allow, they offer an economical and energy efficient measures in order to reduce heating and cooling demand.

The system usually consists of smooth-walled and plastic-coated pipes coated inside with an antimicrobial layer to inhibit the potential growth of mould and bacteria within the tubes. They would typically be buried 1.5 to 3m below ground level where, in the UK, the earth temperature stays at 7-12 °C at all times (Figure 19). An open 'fresh air' system is particularly suitable for a Passive House, where outside air is drawn from a filtered air intake through the pipe-work, taking advantage of pre-cooling in the summer and pre-heating in the heating season. With open fresh air systems it is very important that underground cooling tube have an appropriate condensation drain and be installed at a 2-3 degree grade to make sure that condensed water is removed from the tubes.

The efficiency of an EAHX system depends on many factors such as local climate, tube diameter, length and depth, soil type and moisture content, and the thermal performance of the building's envelope. Generally, moist and high-density soil in a shaded area will produce the highest yield. Instead of using a fan to force air through the pipes, a solar chimney can be utilised, relying on natural convection to draw filtered air through the tubes.

Water-to-earth heat exchangers present an alternative to the earth-to-air heat exchanger. The system set-up is similar to that of a geothermal heat pump system in that tubing is embedded horizontally in the soil at a similar depth of the EAHX. Vertical sondes can also be used. Water-to-earth heat exchangers require approximately twice the length of pipe compared to an EAHX. A heat exchanger coil is placed before the air inlet of the MVHR, with a brine liquid such as salted water used as the heat exchanger fluid. Many European installations are now using this set-up due to the ease of installation as it requires no fall or drainage point. Furthermore, the risk of mould building is greatly reduced.

Figure 19 Operating principle of an EAHX system (REHAU 2006)



Operating principle of the air/heat exchanger in Summer *Operating principle of the air/heat exchanger in Winter*

For this case study, an attempt has been made to model the EAHX in TAS. REHAU Awadukt software was used to size the required system. Calculation results are summarised in the Appendix. The recommended system is a ground to air heat exchanger made from polypropylene (PP) pipes of 200mm diameter over a length of 40m (REHAU 2008). The average supply air temperature is 14ºC in summer and 8ºC in winter, respectively. To simplify this for use in TAS, the pipe runs in **Model EAHX** are simulated as a box with the same surface area and similar conductivity of casing and surrounding earth. Furthermore, to simulate the balanced earth temperature, the casing will be surrounded by a conditioned space, with a constant temperature of 13-20ºC in summer, and 6-10ºC in winter. The model should thus be a good representation of the EAHX system as proposed by REHAU software.

7.4 Shading

In the Northern hemisphere, South facing surfaces experience the greatest amount of direct solar radiation. While in the cold months, harvesting of solar gains through glazed surfaces provides free heating. Glazing is typically the area of increased heat loss. It is therefore important to design the glazing type, location and area such that the captured beneficial solar gains outweigh heat loss associated with glazing. In the warm months, however, solar gains should be reduced as much as possible to reduce the risk of overheating. External shading can be designed such that in allows low-angle direct solar radiation penetrating the glazing in winter and mid-season, while cutting out high-angle direct solar radiation in summer Figure 20). Shading is a convenient way of dealing with summer overheating as it can usually be implemented at any time, and varied seasonally.

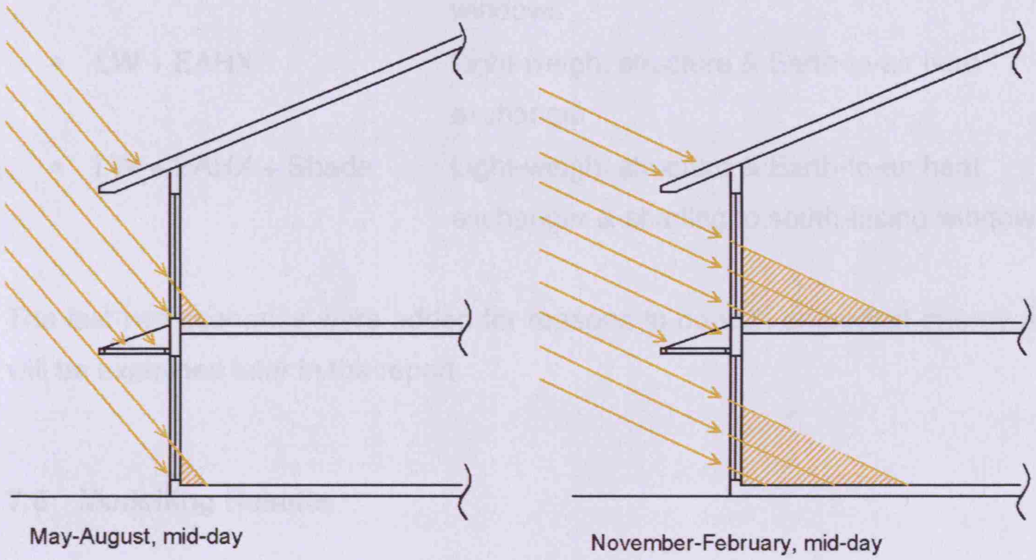


Figure 20 Shading effect - schematics

The Passive Houses in Hannover-Kronsberg have no external shading installed, being one likely cause for temporary overheating of South facing rooms. To test the effect that shading would have on the heating and cooling demand, **Model SHADE1** includes fixed shading elements added to the base case. The shading elements are sized with 'Solar Tool' software with the aim to minimise summer heat gains, while still allowing a high proportion of winter direct solar radiation to enter the building. Details for the shading element design are given in the Appendix.

7.5 Model scenarios

In summary the following scenarios are modelled:

• Base case	Passive House as built in Hannover
• LW	Light-weight building structure, all other properties matching base case
• HW	Heavy-weight building structure, all other properties matching base case
• EAHX	Base case with earth-to-air heat exchanger
• SHADE1	Base case with shading to south-facing windows
• LW + EAHX	Light-weight structure & Earth-to-air heat exchanger
• LW + EAHX + Shade	Light-weight structure & Earth-to-air heat exchanger & shading to south-facing windows

The last two scenarios were added for reasons to do with embodied energy as will be explained later in the report.

7.6 Modelling Results

7.6.1 Temperature

As can be seen in Figures 21 and 22, maximum temperatures vary greatly between the various scenarios. As expected, model LW results in the highest temperatures. In the hottest month July in 2005, it sees a maximum temperature of almost 33ºC, with model HW being roughly 3°C lower. The base case represents an average between LW and HW. It is interesting to see that the light-weight structure with passive design features generally perform as well as the base case or are even better, expect for the month of July.

By 2080, the difference between HW and LW in July increases to almost 4°C, but the relationship between the different scenarios stays about the same.

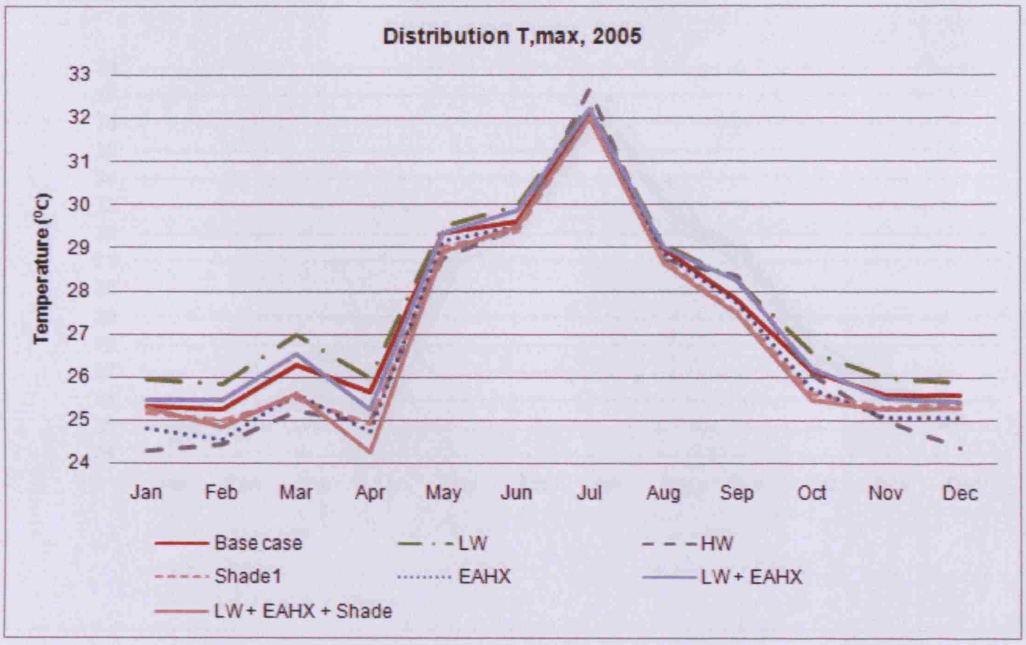


Figure 21 Maximum temperature distribution without comfort cooling for today's climate

7.6.2 Heating demand

Tables 6 and 7 summarise estimated monthly heating demands for each of the scenarios modelled for 2005 (current climate conditions) and 2080 respectively. The base case in combination with the EAHX results in the lowest heating demand today, due to the preheating of incoming air, even though the pre-heating potential of 70 kWh/yr as calculated with TAS appears to be an underestimate when compared with the 250 kWh/yr predicted with REHAU software (see Appendix A10).

The thermal mass of the base case building does contribute to the low heating demand as well, outperforming the light-framed building with and without EAHX. The high thermal mass building model HW stands out as its heating demand is up to 6 times higher than the other scenarios. Generally it can be seen that in 2080 monthly heating demand is reduced from 30% for model HW, up to 70% for the other scenarios. HW is still by far the highest heating energy consumer.

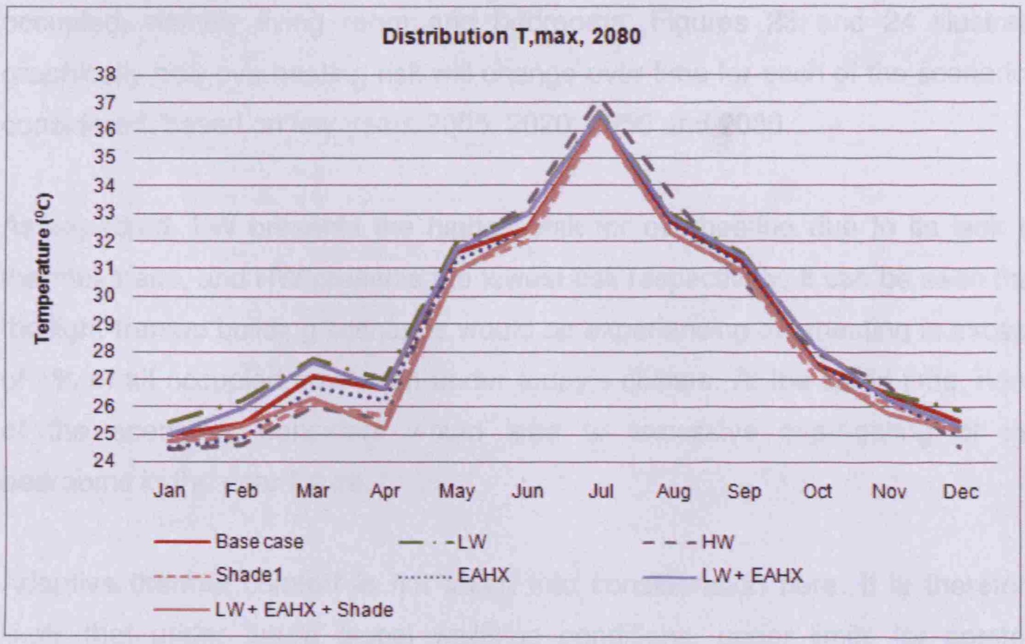


Figure 22 Maximum temperature distribution without comfort cooling predicted for 2080

Table 6 Estimated heating demand in 2005 for each scenario

Heating demand 2005	Base case	LW	HW	Shade1	EAHX	LW + EAHX	LW + EAHX + Shade
Jan	151	150	604	162	136	139	149
Feb	106	109	559	125	89	94	115
Mar	45	42	416	69	34	33	56
Apr	0	0	185	4	0	0	3
May	0	0	16	0	0	0	0
Jun	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0
Oct	0	0	78	0	0	0	0
Nov	33	57	373	46	22	48	58
Dec	142	151	599	152	125	138	148
Total (kWh)	**478**	**510**	**2830**	**558**	**406**	**453**	**529**

7.6.3 Overheating risk

In order to keep energy demand and thus CO_2 emissions to a minimum, comfort cooling should not be utilised as long as comfort conditions can be maintained without it. Based on comfort temperatures are defined in Table 3, the TAS modelling results are used to assess overheating risk for spaces that are most occupied, namely living room and bedrooms. Figures 23 and 24 illustrate graphically how overheating risk will change over time for each of the scenarios considered, based on key years 2005, 2020, 2050 and 2080.

As expected, LW presents the highest risk for overheating due to its lack of thermal mass, and HW presents the lowest risk respectively. It can be seen that the light-framed building scenarios would be experiencing overheating in excess of 1% of all occupied time even under today's climate. At the same time, none of the scenarios considers would lead to excessive overheating of the bedrooms in the near future.

Adaptive thermal comfort is not taken into consideration here. It is therefore likely that under future global warming conditions, upper limits for comfort temperatures can be corrected upwards. However, it must be assumed that occupants will install comfort cooling once a certain overheating threshold is exceeded. Thermal comfort is rather subjective, and it is impossible to predict when occupants will decide to switch to comfort cooling. The next chapter summarises what comfort cooling would mean in terms of energy demand.

Table 7 Estimated heating demand in 2080 for each scenario

Heating demand 2080	Base case	LW	HW	Shade1	EAHX	LW + EAHX	LW + EAHX + Shade
Jan	68.6	70.0	446.2	78.0	61.9	64.3	73.1
Feb	36.1	44.8	408.8	50.9	27.6	35.2	49.6
Mar	7.7	5.9	285.9	17.1	4.3	3.4	10.8
Apr	0.0	0.0	53.4	0.0	0.0	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	0.0	2.9	124.3	0.0	0.0	1.4	3.5
Dec	33.1	54.3	392.6	42.2	26.5	47.6	55.4
Total (kWh)	145	178	1711	188	120	152	192

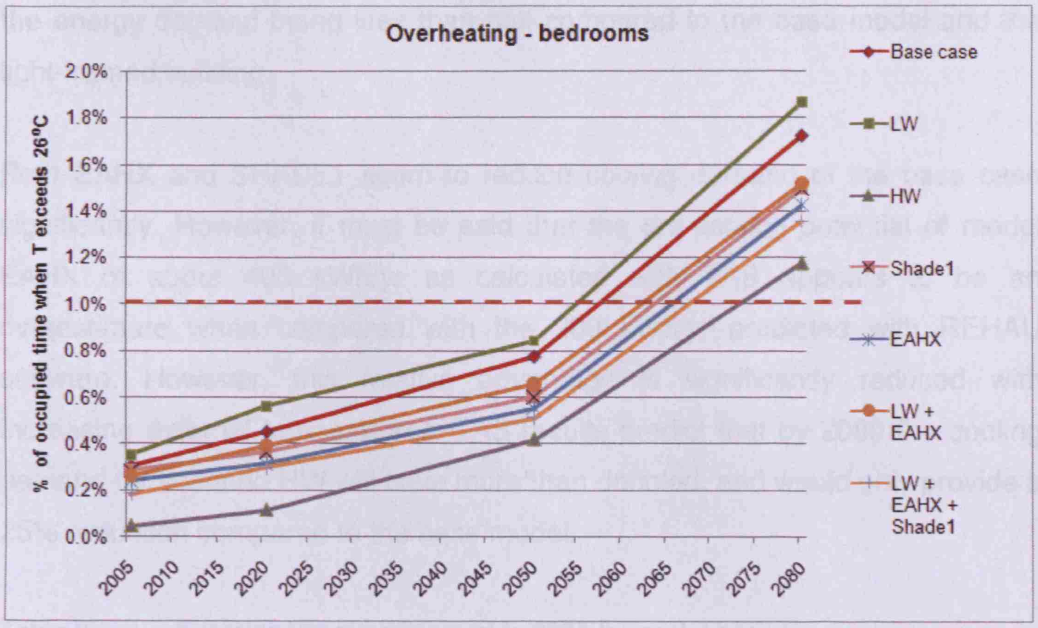


Figure 23 Overheating risk for bedrooms over time

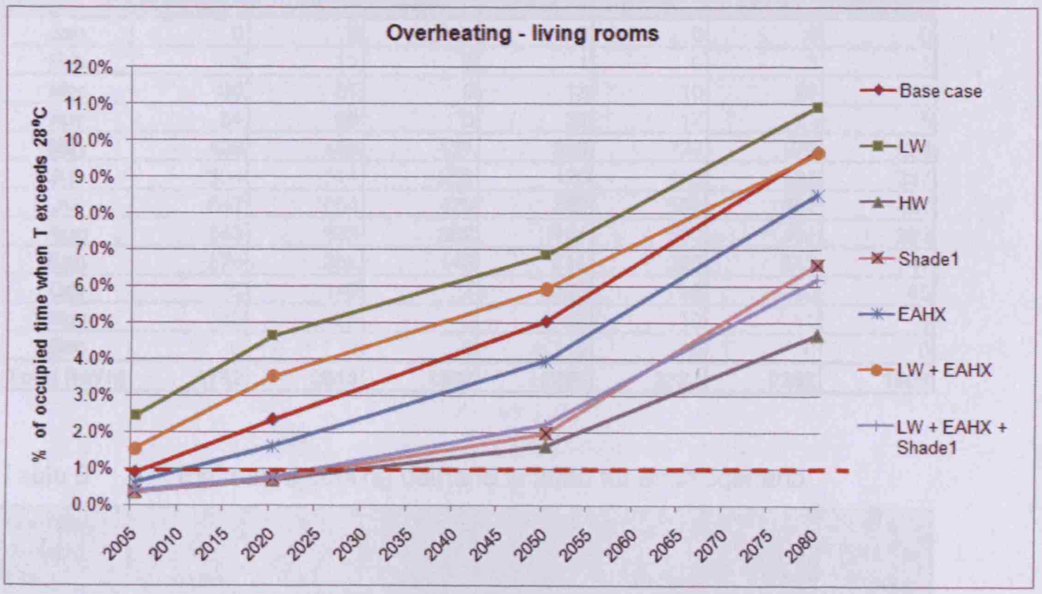


Figure 24 Overheating risk for living room over time

7.6.4 Cooling demand

Tables 8 and 9 summarise estimated monthly cooling demands for each of the scenarios modelled for current climate conditions and 2080 respectively. It shows that if comfort cooling was utilised today, HW is performing very well with the energy demand being less than half compared to the base model and the light-framed building.

Both EAHX and SHADE1 seem to reduce cooling demand of the base case significantly. However, it must be said that the pre-cooling potential of model EAHX of about 400 kWh/yr as calculated with TAS appears to be an overestimate when compared with the 200 kWh/yr predicted with REHAU software. However, this relative advantage is significantly reduced with increasing external temperatures. TAS results predict that by 2080 the cooling demand for scenario HW will have more than doubled, and would only provide a 25% reduction compared to the base model.

Table 8 Estimated cooling demand in 2005 for each scenario

Cooling demand 2005	Base case	LW	HW	Shade1	EAHX	LW + EAHX	LW + EAHX + Shade
Jan	0	0	0	0	0	0	0
Feb	3	12	0	1	0	3	1
Mar	30	51	0	13	10	25	10
Apr	64	68	0	31	17	24	5
May	428	453	131	329	339	372	254
Jun	504	511	259	420	428	432	337
Jul	647	654	479	552	595	602	487
Aug	543	533	362	461	500	491	393
Sep	376	358	143	316	328	313	247
Oct	155	146	7	123	95	90	65
Nov	32	25	0	22	12	11	6
Dec	0	2	0	0	0	0	0
Total (kWh)	2782	2813	1382	2269	2324	2362	1805

Table 9 Estimated cooling demand in 2080 for each scenario

Cooling demand 2080	Base case	LW	HW	Shade1	EAHX	LW + EAHX	LW + EAHX + Shade
Jan	3	7	0	1	0	1	0
Feb	26	41	0	15	5	14	7
Mar	102	123	2	68	43	64	35
Apr	174	173	2	116	97	98	48
May	608	636	329	498	540	565	430
Jun	730	728	565	630	667	664	551
Jul	903	906	884	790	872	875	736
Aug	803	799	763	702	785	780	660
Sep	623	610	523	552	600	585	505
Oct	343	325	128	306	305	289	250
Nov	115	101	10	95	79	69	54
Dec	9	15	0	6	1	3	2
Total (kWh)	4439	4464	3205	3780	3996	4007	3279

As mentioned earlier in the report, adaptive thermal comfort is not taken into consideration. Cooling demands predicted for 2050 and 2080 are thus likely to be an overestimate. Nevertheless, the cooling demand is estimated to still be considerably higher than heating demand.

7.7 Result interpretation

The modelling results show that overheating risk is problematic for both the base case and LW under today's climate. The risk is increasing over time for all scenarios. Furthermore, energy required for comfort cooling is significant for all scenarios, and the required amount increasing over time.

The various scenarios considered lead to quite different results in terms of overheating risk, heating demand and cooling demand. To be able to quantitatively compare the scenarios in regards to their overall operational energy demand, each building variation is assessed over its predicted lifetime of 60 years. The time period chosen is 2010 to 2069 to represent new-built Passive House today and in the near future.

As was mentioned earlier, it is impossible to know when occupants will install comfort cooling. For this study it is assumed that occupants will switch to comfort cooling for the entire house the year after the overheating criteria in either bedrooms or living room as defined in Table 3 can not be fulfilled. Tables 10 and 11 summarise the predicted overheating risk for each key year and each scenario modelled. According to the Tables, the base case as well as scenarios LW and LW + EAHX require comfort cooling from the beginning, while other scenarios will utilise comfort cooling at a later point.

Energy required for cooling is calculated from the first year of use, and averaged over the relevant time period. Heating will be required over the lifetime of buildings. For this study the total heating energy demand is averaged over time, based on the key years modelled. A summary of all operational energy demand for heating and cooling for each of the scenarios is given in Table 12. The results show that scenario HW would lead to a decrease in operational energy demand of just 3% compared to thee base case. However, shading of the south-facing windows of the base case could lead to an almost 40% reduction. The best improvement of roughly 50% is achieved with the light-framed building in combination with shading and EAHX. The light-framed building by itself, in contrast, would lead to a 14% increase in energy demand.

Table 10 Overheating risk over time - bedrooms

Overheating Risk - Bedroom	2005	2020	2050	2080	year of first overheating
Base case	0.3%	0.4%	0.8%	1.7%	2057
LW	0.4%	0.6%	0.8%	1.9%	2054
HW	0.0%	0.1%	0.4%	1.2%	2072
Shade1	0.3%	0.4%	0.6%	1.5%	2063
EAHX	0.2%	0.3%	0.6%	1.4%	2065
LW + EAHX	0.3%	0.4%	0.7%	1.5%	2062
LW + EAHX + Shade1	0.2%	0.3%	0.5%	1.4%	2067

Table 11 Overheating risk over time - living room

Overheating Risk - Living room	2005	2020	2050	2080	year of first overheating
Base case	0.9%	2.3%	5.0%	9.7%	2006
LW	2.5%	4.7%	6.9%	10.9%	1995
HW	0.4%	0.7%	1.6%	4.7%	2032
Shade1	0.4%	0.7%	2.0%	6.6%	2030
EAHX	0.6%	1.6%	4.0%	8.5%	2010
LW + EAHX	1.5%	3.5%	5.9%	9.6%	2000
LW + EAHX + Shade1	0.4%	0.8%	2.2%	6.2%	2029

The buildings energy demand varies from roughly 2.2 MWh/yr to 4.7 MWh/yr. This translates to 18-39 kWh/m^2/yr. This means that based on the results of this study it must be concluded that the Passive House limit of 15 kWh/m^2/yr can not be met by any of the scenarios under future climate change conditions.

CO_2 emissions can vary greatly, depending on the method with which the energy is generated and the type of fossil fuel used. For this comparison, the carbon factors used for operational energy are based on national standards (DEFRA, BRE, & ODPM 2008). The factors are expected to change over time due to changes in the fossil fuel mix and the increased reliance on renewable energy. It is impossible to predict them at this stage though. For this reason and to simplify the calculations, the factors are kept constant throughout the calculations.

For the purpose of this study a reverse-cycle air-source heat pump system is applied, and both the seasonal coefficient of performance for space heating (COP) and the seasonal energy efficiency ratio for space cooling (EER) are assumed as 3.5. The results are also summarised in Table 12. As both heating and cooling efficiencies are taken as the same, relative improvements compared to the base case are the same as was for the energy demand.

As addressed earlier, another main difference between the different scenarios besides thermal performance is their embodied content. The next chapter contains an embodied energy study for each or the scenarios.

Table 12 Operational energy and CO_2 emissions comparison

Comparative study - Energy and CO2 related to heating/cooling demand	Model name	Energy				CO2		
		Annual heating demand * (MWh)	Annual cooling demand * (MWh)	Annual total (MWh)	Percentage reduction in energy demand over base case	Annual CO2 emissions due to heating (tCO2) **	Annual CO2 emissions due to cooling (tCO2) **	Percentage improvement over base case (CO2)
Passive house Hannover-Kronsberg	base case	0.31	3.82	4.12	n/a	0.037	0.460	n/a
Light-weight structure	LW	0.36	4.34	4.70	-14.0%	0.043	0.523	-14.0%
Heavy-weight structure	HW	2.44	1.54	3.98	3.3%	0.294	0.186	3.3%
Passive house - shading on south side	SHADE1	0.39	2.10	2.49	39.6%	0.047	0.253	39.6%
Passive house with EAHX	EAHX	0.28	2.99	3.27	20.7%	0.034	0.360	20.7%
Light-weight with EAHX	LW + EAHX	0.32	3.52	3.83	7.0%	0.038	0.424	7.0%
Light-weight with EAHX & shading on South side	LW + EAHX + Shade1	0.38	1.82	2.19	46.8%	0.046	0.219	46.8%

* averaged over 60 year lifespan for structure (2010-2069)

** Carbon factor used is 0.422 kg CO2/kWh for heating & cooling (heat pump, electric, COP=3.5)

8 Embodied Energy Analysis

8.1 Significance of Embodied Energy

The build environment is a mayor consumer of resources and as considerably contributes to man-made CO_2 emissions. Other studies suggest that buildings are responsible for almost half of UK carbon emissions, half of water consumption, about one third of landfill waste and 13% of all raw materials used in the UK economy (BERR, DEFRA, DCLG, & DCMS 2007). Besides energy needed to operate a building, it is the energy embodied in the building itself that makes up a significant amount of the UK's CO_2 emissions.

Embodied energy is the energy needed to construct a building, including the procurement of raw materials, manufacture, transport, construction, maintenance and repair. The amount of embodied energy and CO_2 in a building can vary greatly depending on materials and construction techniques chosen. Portland cement for example, one of the main ingredients of conventional concrete mixes, is extremely carbon intensive with almost one ton of CO_2 emitted for each ton of cement produced. Timber on the other hand captures CO_2 during tree growth, therefore leading to very low emissions due to production, or even negative emissions in some cases.

Figures 25 and 26 summarise embodied energy and embodied CO_2 values for common building materials. It can be seen that finishing materials such as copper for cladding, or floor finishes such as carpets and vinyl flooring have a high embodied energy and embodied CO_2 content. The quantity of finishing materials used is usually a lot less than the quantity of materials used for the main structure. However, while the main structure stays in place over the lifetime of the building (here assumed as 60 years), carpets for example are replaced every 10-15 years. It is this shorter lifespan that in many cases makes the CO_2 content of finishing materials over the lifetime of the building as high of even higher than that of the main structure.

This study is focusing on the impacts of the main building structure. The embodied energy and CO_2 is counted 'from cradle to site', thus excluding construction processes on site. This is done as reliable data for construction is not available, and the amount should in general be neglect able in comparison with production and transport processes. Following is a description of the methodology used to assess embodied energy and CO_2.

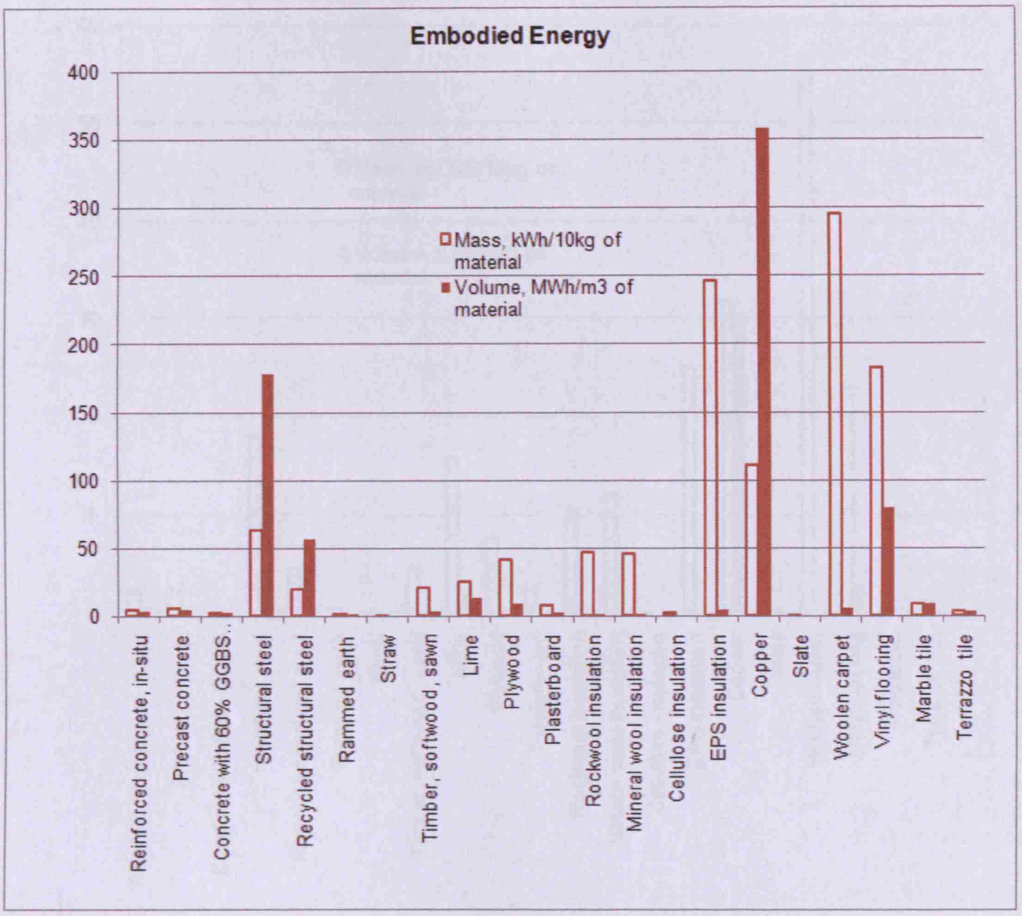


Figure 25 Embodied energy ('cradle to site') in common building materials (Hammond & Jones 2005)

8.2 Methodology

This study quantitatively compares operational energy saved or added due to thermal mass with the energy associated with that same thermal mass. It is not attempted here to account for the entire amount of energy embedded in a building. Instead, this study focuses purely on the energy embodied in materials that were varied in the thermal modelling analysis and would have an impact on the thermal mass performance. These include the main structure used for walls and floors, including internal finishes such floor tiles, screeds and plasterboard. They exclude insulation materials and elements located at the external side of the main insulations layer, e.g. external cladding.

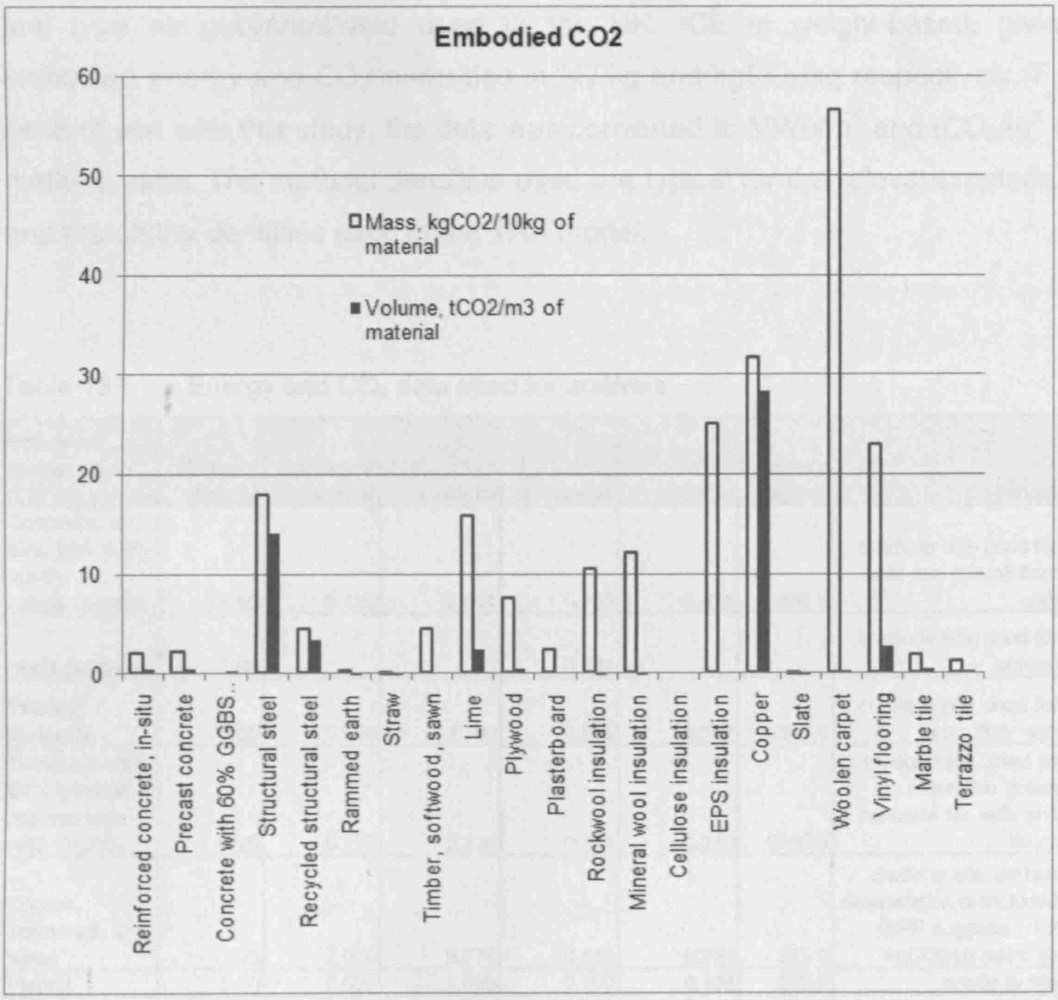


Figure 26 Embodied CO_2 ('cradle to site') in common building materials (Hammond & Jones 2005)

To quantify the amount of energy and CO_2 embodied in the thermal mass elements this study relies on data published in the 'Inventory of Carbon & Energy' (ICE) published by the University of Bath (Hammond & Jones 2005). The boundary conditions for the data are 'cradle to site', including activities from extraction of raw materials over the finished product to the transport to site. All energy use is traced back to the earth in primary equivalents. Excluded is energy use in relation to transport from factory to site, construction on site, and maintenance. CO_2 emissions were calculated based on the typical fuel split in the relevant industry sector as defined by DTI, and carbon intensity factors per fuel type as published and used in the UK. ICE is weight-based, giving embodied energy and CO_2 intensities in MJ/kg and $kgCO_2/kg$ respectively. For ease of use with this study, the data was converted to MWh/m^3 and tCO_2/m^3 of material used. The material densities used are typical for the relevant materials and match the densities used in the TAS model.

Table 13 Energy and CO_2 data used for analysis

Embodied energy and CO2	MJ/kg of material	kWh/kg of material	MWh/m3 of material	kgCO2/kg of material	tCO2/m3 of material	Density (kg/m3)	Comment
Concrete, in-situ, incl. 0.5% steel reinforcement	1.53	0.425	**3.611**	0.199	**0.470**	2360.0	cradle to site, used for walls and ground floor slab
Mass concrete	0.99			0.134			cradle to site, used for screed
Precast concrete	2.00	0.556	**4.720**	0.215	**0.507**	2360.0	cradle to site, used for upper floor slab
Concrete with 60% cement replacement with GGBS	0.99	0.275	**2.336**	0.134	**0.316**	2360.0	cradle to site, used as alternative 'green concrete' for walls and floors
Timber, softwood, dry, sawn	7.40	2.056	**3.774**	0.440	**0.224**	510.0	cradle to site, carbon sequestation is excluded (BRE suggests -1.2 kgCO2/kg material)
Plaster	1.80	0.500	**1.528**	0.160	**0.136**	849.0	cradle to site
Plywood	15.00	4.167	**8.250**	0.750	**0.413**	550.0	cradle to site
Plasterboard	2.70	0.750	**2.592**	0.240	**0.230**	960.0	cradle to site
Terrazzo tile	1.40	0.389	**3.360**	0.118	**0.283**	2400.0	cradle to site
Soil excavation and backfilling	-	-	-	-	-	-	impact on EAHX, data not available and neglectable
Polyprolylene (PP)	84.4	23.444	**75.960**	2	**1.800**	900	data not available, HDPE data used instead, cradle to gate data

8.3 Embodied energy and carbon analysis

Material data relevant for the various thermal modelling scenarios is listed in Table 13. Based on these values, embodied energy and CO_2 is compiled in Tables 14 and 15 respectively. Detailed calculations for each scenario are given in Appendix A9.

The results in Table 14 reveal that the scenario with the lowest embodied energy and CO_2 is the timber-framed structure followed the same building in combination with EAHX and shading elements. The concrete framed building in comparison has highest content, with the embodied CO_2 more than six times that of the light-weight structure, and almost doubling the CO_2 content of the base case. The carbon intensity of both the concrete elements and the shading devices stand out as having a significant impact on the embodied energy and CO_2. This is mainly due to the energy and carbon intensity of both Portland cement assumed for the concrete mix, and stainless steel assumed for the shading devices.

Table 14 Energy content per main building element for each scenario

Embodied energy study	Model name	Embodied energy - external walls (MWh)	Embodied energy - internal walls (MWh)	Embodied energy - ground floor (MWh)	Embodied energy - upper floor (MWh)	Other (MWh)	Total (MWh)
Passive house Hannover-Kronsberg	**base case**	13.58	9.99	59.57	50.40	0.00	**133.5**
Light-weight structure	**LW**	13.58	9.99	19.03	21.05	0.00	**63.6**
Heavy-weight structure	**HW**	57.05	67.24	59.57	60.12	0.00	**244.0**
'Green concrete' alternative	*HW ^*	*39.82*	*46.94*	*41.58*	*41.96*	*0.00*	***170.3***
Passive house - shading on south side	**SHADE1**	13.58	9.99	59.57	50.40	23.07	**156.6**
'Green shading' alternative	*SHADE1 ^*	*13.58*	*9.99*	*59.57*	*50.40*	*6.76*	***140.3***
Passive house with EAHX	**EAHX**	13.58	9.99	59.57	50.40	16.71	**150.2**
Light-weight with EAHX	**LW + EAHX**	13.58	9.99	19.03	21.05	16.71	**80.4**
Light-weight with EAHX & shading on South side	**LW + EAHX + Shade1**	18.07	9.99	22.30	27.53	39.78	**117.7**

In the built environment there are many alternative materials that can be used to decrease energy and carbon intensity, including timber, reused and recycled products. For the purpose of this study, alternative materials are tested that have significantly lower embodied energy and carbon but would not change operational energy demand. For the concrete this entails replacing 60% of Portland cement with ground-granulated blast furnace slag (GGBS). GGBS is a waste product from the steel industry and as such its embodied energy and carbon is very low. Overall, 60% replacement of cement with GGBS will result in halving embodied CO_2 of the concrete mix. Table 13 contains the amount of energy and CO_2 embodied in the main elements if GGBS was used in the concrete mix. The effect that partially replacing the stainless steel shading devices with timber elements would have is also analysed, and results are presented in Tables 14 and 15.

Table 15 CO_2 content of each main building element for each scenario

Embodied CO2	Model name	Embodied CO2 - external walls (tCO2)	Embodied CO2 - internal walls (tCO2)	Embodied CO2 - ground floor (tCO2)	Embodied CO2 - upper floor (tCO2)	Other (tCO2)	Total (tCO2)
Passive house Hannover-Kronsberg	base case	0.88	0.76	7.60	5.16	0.00	**14.4**
Light-weight structure	LW	0.88	0.76	1.07	1.25	0.00	**4.0**
Heavy-weight structure	HW	6.10	7.15	7.60	6.62	0.00	**27.5**
'Green concrete' alternative	*HW ^*	*4.67*	*5.48*	*5.82*	*5.07*	*0.00*	***21.0***
Passive house - shading on south side	SHADE1	0.88	0.76	7.60	5.16	2.76	**17.2**
'Green shading' alternative	SHADE1 ^	0.88	0.76	7.60	5.16	0.65	**15.1**
Passive house with EAHX	EAHX	0.88	0.76	7.60	5.16	0.40	**14.8**
Light-weight with EAHX	LW + EAHX	0.88	0.76	1.07	1.25	0.40	**4.4**
Light-weight with EAHX & shading on South side	LW + EAHX + Shade1	0.88	0.76	1.07	1.25	3.15	**7.1**

Just these two examples demonstrate the potential that alternative 'green' materials could have on the total embodied energy and CO_2 of a building structure. The question is how much is the relative impact that the selection of the materials has on the total energy demand and CO_2 emissions over the lifetime of the building. To answer this question, the results have to be compared against the operational energy demand caused by the variation in building elements. This is done in the next chapter.

9 Result analysis

This study compares CO_2 emissions due to both operational and embodied energy over the lifespan of the building if it was built in 2010. The lifespan is assumed as 60 years, a time period commonly used for buildings. For the purpose of this study heating energy demand is averaged over the lifespan of the building from 2010 to 2069, based on the energy demands determined with linear interpolation for key years 2005, 2020, 2050 and 2080.

It is assumed that as long as overheating criteria are met, no comfort cooling is used. Comfort cooling is applied from the year after overheating criteria are not met for any of the relevant rooms , and cooling energy demand averaged over the time period from when comfort cooling is first required until 2069 (see Chapter 7). To estimate related CO_2 emissions, the carbon factors used for operational energy are based on national standards (DEFRA, BRE, & ODPM 2008).

Energy and CO_2 intensities for building materials are obtained from data collected by the University of Bath (Hammond & Jones 2005). These figures include for typical fuel type use and conversion efficiencies in the relevant industries. Considered here are only those building elements that vary between the different scenarios and thus contribute to the changes in heating demand and cooling demand (see Chapter 7).

The total energy demand and CO2 emissions are calculated for the base case and all variation considered earlier in both the TAS study and the embodied energy study. Tables 16 and 17 summarise the results and gives the relative improvement of all variations over the base study, both in terms of energy and CO_2.

The results suggest that the light-weight structure by itself does not offer significant advantages or disadvantages compared to the base case. Combined with passive design measures such as the EAHX and shading of the South-facing windows, however, it can achieve improvement over more than 35% and 48% in reduction of energy demand and CO_2 emissions respectively. Even the base case can be improved by 20-25% through the addition of shading, depending on the material used.

Table 16 Comparative study – energy

Comparative study - energy demand	Model name	Energy			
		Total heating / cooling demand * (MWh)	Total embodied energy - main elements (MWh)	Total energy demand (MWh)	Percentage reduction in energy demand over base case
Passive house Hannover-Kronsberg	base case	247	134	381	n/a
Light-weight structure	LW	282	64	346	9%
Heavy-weight structure	HW	239	244	483	-27%
'Green concrete' alternative	*HW ^*	*239*	*170*	*409*	*-7%*
Passive house - shading on south side	SHADE1	149	157	306	20%
'Green shading' alternative	*SHADE1 ^*	*149*	*140*	*290*	*24%*
Passive house with EAHX	EAHX	196	150	346	9%
Light-weight with EAHX	LW + EAHX	230	80	310	19%
Light-weight with EAHX & shading on South side	LW + EAHX + Shade1	132	118	249	35%

* based on 60 year lifespan for structure

^ use of alternative materials without changing thermal properties of building

The high thermal mass building does not lead to an improvement over the base case if conventional concrete was to be used. Even replacing the conventional concrete with GGBS concrete would still result in higher energy demand and increased CO_2 emissions when compared to the base case.

Table 17 Comparative study – CO_2

Comparative study - CO2 emissions	Model name	CO2 emissions due to heating / cooling (tCO2) *	Embodied CO2 emissions - main elements (tCO2) *	Total CO2 emissions, operational + embodied (tCO2) **	Percentage improvement over base case (CO2)
Passive house Hannover-Kronsberg	**base case**	30	14	44	n/a
Light-weight structure	**LW**	34	4	38	**14%**
Heavy-weight structure	**HW**	29	27	56	**-27%**
'Green concrete' alternative	*HW ^*	29	21	50	**-13%**
Passive house - shading on south side	**SHADE1**	18	17	35	**20%**
'Green shading' alternative	*SHADE1 ^*	18	15	33	***25%***
Passive house with EAHX	**EAHX**	24	15	38	**13%**
Light-weight with EAHX	**LW + EAHX**	28	4	32	**27%**
Light-weight with EAHX & shading on South side	**LW + EAHX + Shade1**	16	7	23	**48%**

* based on 60 year lifespan for structure

** Carbon factors used for embodied energy are per ICE

^ use of alternative materials without changing thermal properties of building

All other scenarios offer an improvement over the base case, with the light-framed building with EAHX and shading achieving the highest reduction in energy demand and CO_2 emissions of 35% and 48% respectively.

Many assumptions and simplifications had to be made for this study. The most significant once and their likely impact on the results are as follows:

1. Inaccuracy of climate change predictions: This could lead to either overestimation or underestimation of energy demand for heating and cooling;
2. Change in carbon intensity of energy supplied from heating and cooling in future: The increased use of renewable energy sources as proposed by the UK government is not considered here, and would

result in a decrease of CO_2 emissions related to future heating and cooling;

3. Change in thermal comfort criteria over time: As adaptive thermal comfort is not taken into consideration in this study, both overheating times and energy demand for cooling are likely to be overestimated;
4. Effectiveness of thermal mass in residential buildings: Occupant behaviour, e.g. inappropriate opening of windows and covering of thermal mass elements could compromise potential reduction in cooling demand;
5. Effectiveness of EAHX: As the earth temperatures used in the TAS models are not adjusted to take into account increasing external temperatures, the effectiveness of the EAHX is likely to be an overestimation both in terms of pre-heating and pre-cooling capacity;
6. Accuracy of ICE data: Although the data used covers embodied energy and CO_2 from 'cradle to site', actual figures could vary greatly depending on supplier and also the transport distance from factory to site, therefore either overestimating or underestimating embodied energy and CO_2.

Furthermore, there are a large number of other factors that have an impact particularly on the energy demand for heating and cooling that makes it very difficult to apply the findings to other dwellings in the UK. The main factors to name a few are dwelling size and shape, the ratio of exposed dwelling surfaces to dwelling volume, local climate variations, window sizes and orientation.

Last but not least, the nature of the building, local conditions and restrictions might dictate what building materials can be used. Particularly the main structure of the building is dependent on other performance requirement such as structural integrity and fire safety. The possibility of using green materials such as timber, straw or rammed earth can therefore be limited. In addition, the utilisation of EAHX systems depends on available space.

Taking all the above into consideration, the study demonstrates that embodied energy and embodied CO_2 play an important role in the overall energy use and

CO_2 emissions over the lifetime of a dwelling built to Passive House standard. Passive design measures aiming to reduce operational energy demand need therefore be weighted against their embodied energy impact to determine the net lifetime benefit of such measure.

10 Conclusion

In the housing sector Passive Houses are an appropriate strategy to achieve the desired 60% CO_2 reduction by 2050, compared to 1990 levels. This study demonstrates how reductions of more than 60% can be achieved today compared to the existing building stock if all UK dwellings were either built to, or refurbished to Passive House standard. Furthermore, Passive Houses present an option to reduce space heating demand per heating area by almost 90% compared to 1990 levels. All this is based on 'steady state' conditions under which climate conditions and thus predicted heating and cooling demand do not change.

With increasing temperatures due to climate change, the design of Passive House, as much as the design for all other types of new-builds and major refurbishments, should focus on the prevention of summertime overheating. The results of this study suggest that based on current climate change prediction for the London area, cooling demand is likely to outweigh by far the need for space heating over the cause of this century.

Heavy thermal mass is one passive design measure that is used to limit the risk for overheating in dwellings. Its capability of temporarily storing excessive internal heat during hot sunny days, and releasing it at night appears to be a suitable strategy in counteracting increased overheating risk in the future. However, this study and works by others indicate that high thermal mass dwellings generally require more energy for space heating, and only have a small positive impact on cooling energy demand once comfort cooling is utilised. Furthermore, thermal mass elements tend to have higher embodied energy content than their light-weight alternatives. The study aims to determine if the use of thermal mass would result in a net energy saving and net CO_2 reduction considering both operational and embodied energy over the lifetime of a dwelling.

Based on modelling results and embodied energy estimates for one Passive House over a 60 year building lifespan, this study comes to the conclusion that the achievement of net energy savings and net CO_2 reductions can depend as much on the energy embodied in the main building elements as it does depend on changes in thermal performance that these main building elements can produce.

This study confirms that building elements of high thermal mass can significantly reduce overheating risk of this particular Passive Houses. It also indicates that the lifetime operational energy savings are likely to be better than those of building with little thermal mass. When looking at the total energy savings over the lifespan of the dwelling, however, buildings with low embodied energy outperform those with energy-intensive high thermal mass. Other passive design measures such as shading and EAHX can lower the overheating risk as well as thermal mass and generally come with a significantly lower embodied energy burden.

This analysis is based on a large number of simplifications, mainly due to lack of reliable data. Despite this fact, the relevance of embodied energy and CO_2 in main building elements has been demonstrated. Its importance in the battle to fight climate change needs to be considered as important during design as is operational energy. This is the same for the selection of finishing materials as their energy and CO_2 intensity together with their shorter lifespan can outweigh that on the main structure over the lifetime of the building.

It is very likely that energy will be less carbon intensive in the future due to a higher percentage provided by renewables. Furthermore, any emissions incurred today have a more negative impact on global warming due to positive feedback that emissions incurred in the future. If both are taken into consideration, the significance of CO_2 embodied in the main building structure increases ever so more. More research is needed to quantify the benefits that reuse of building elements in-situ and the use of green building materials have to offer.

In any case, implementing the Passive House Standard in the UK housing sector would clearly have great potential within the overall strategy to stabilise or even reverse global warming.

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Appendix

A1 Base case results

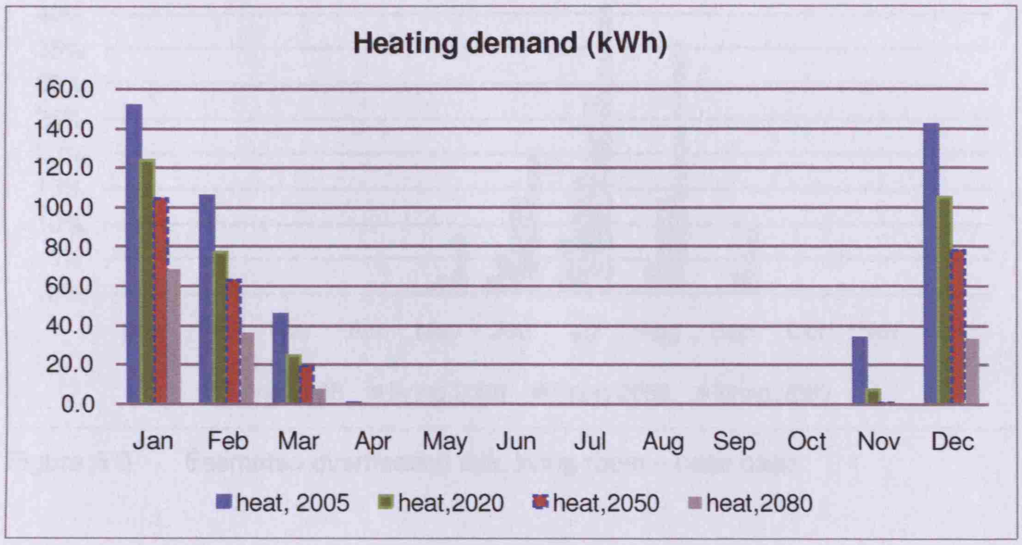


Figure A 1 Estimated heating demand – base case

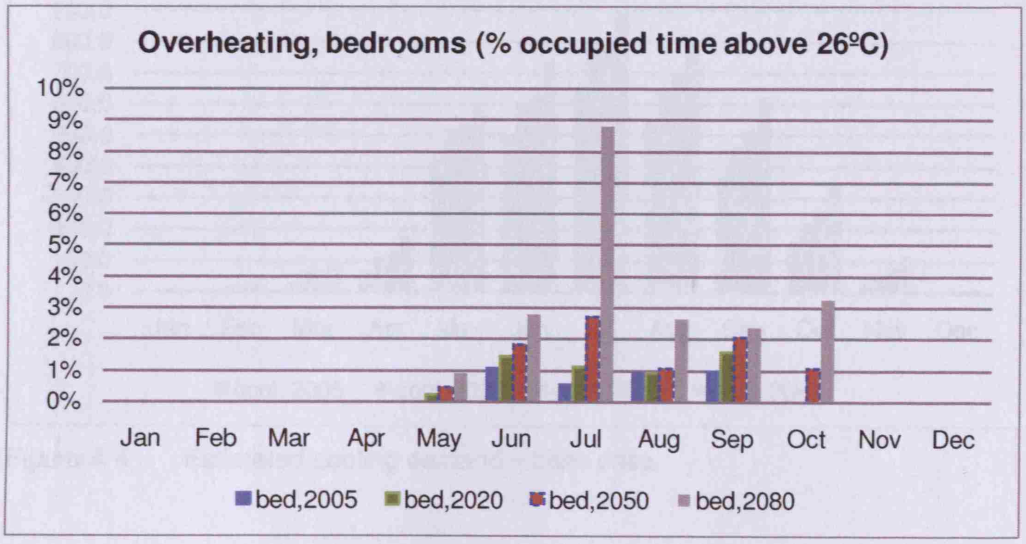


Figure A 2 Estimated overheating risk, bedrooms – base case

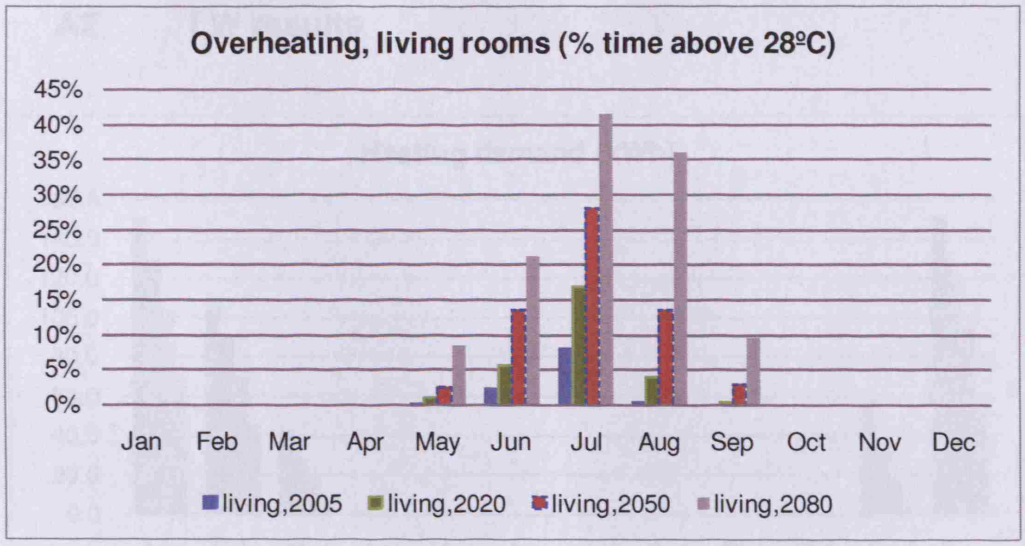


Figure A 3 Estimated overheating risk, living room – base case

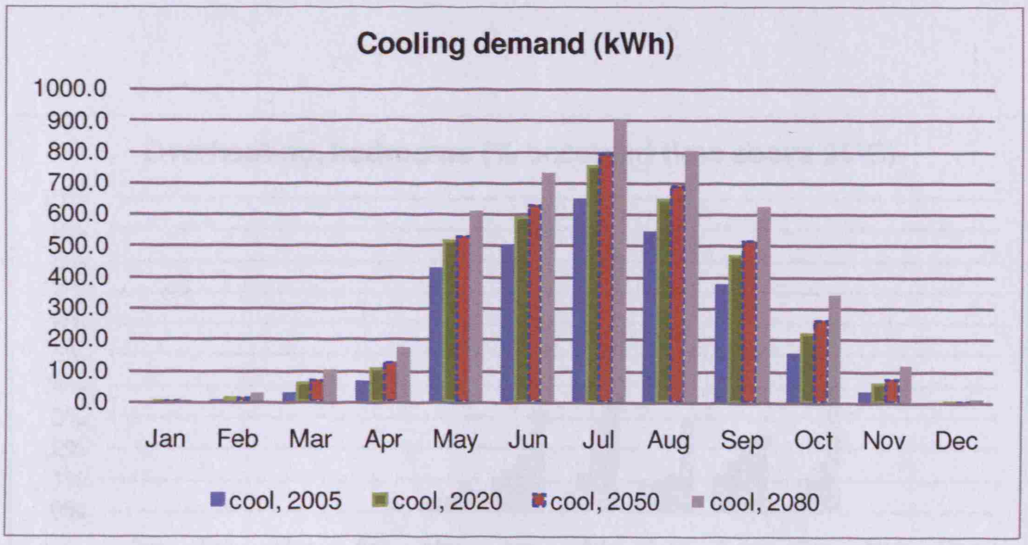


Figure A 4 Estimated cooling demand – base case

A2 LW results

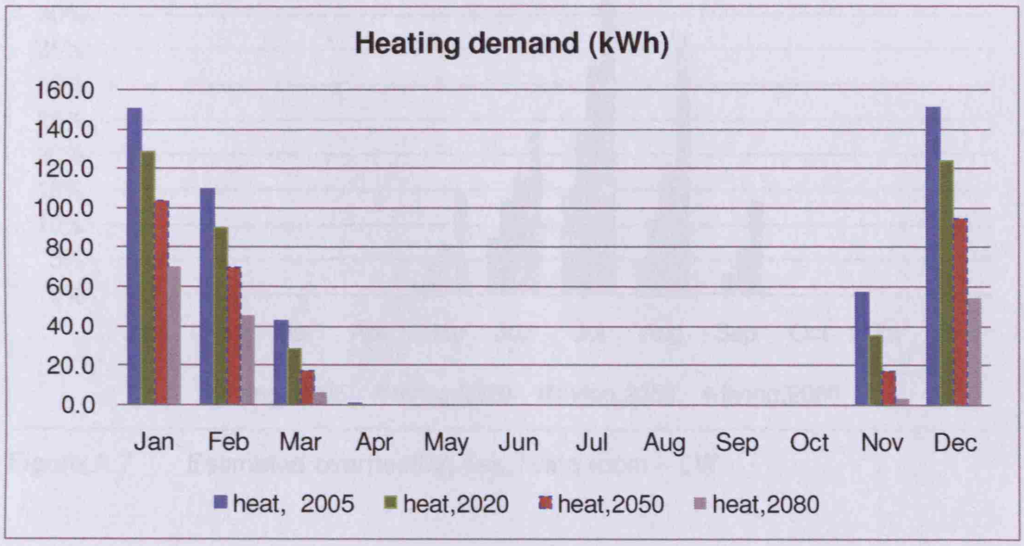


Figure A 5 Estimated heating demand – LW

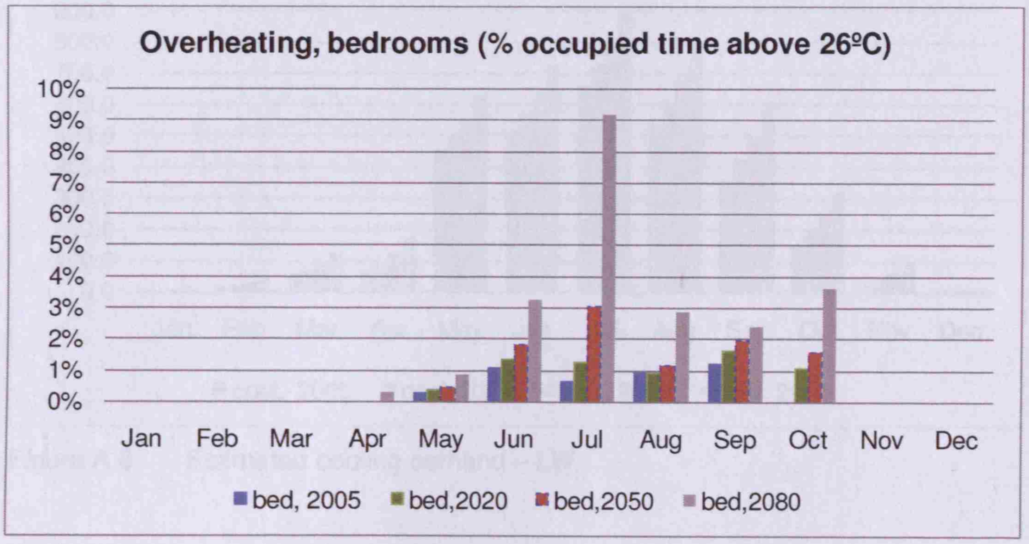


Figure A 6 Estimated overheating risk, bedrooms – LW

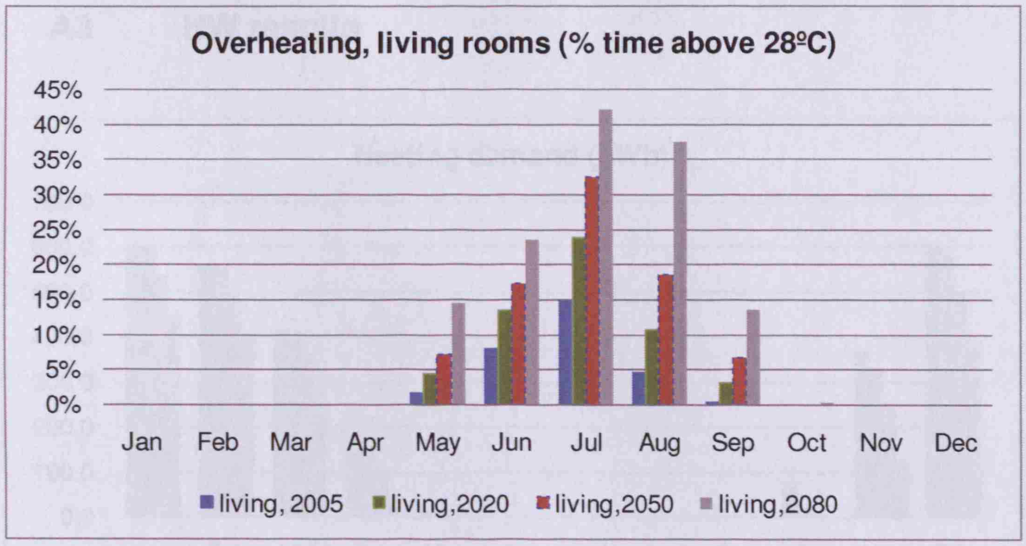


Figure A 7 Estimated overheating risk, living room – LW

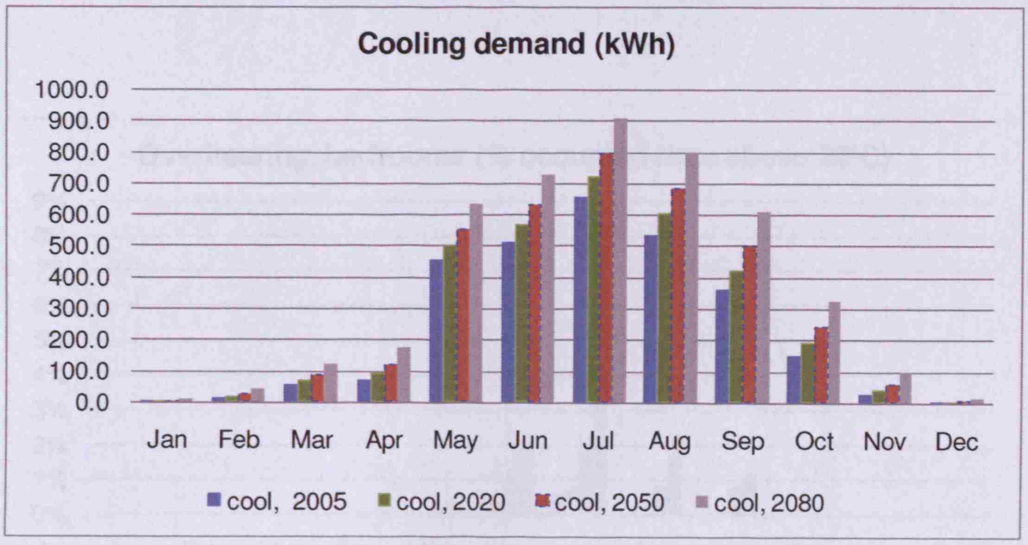


Figure A 8 Estimated cooling demand – LW

A3 HW results

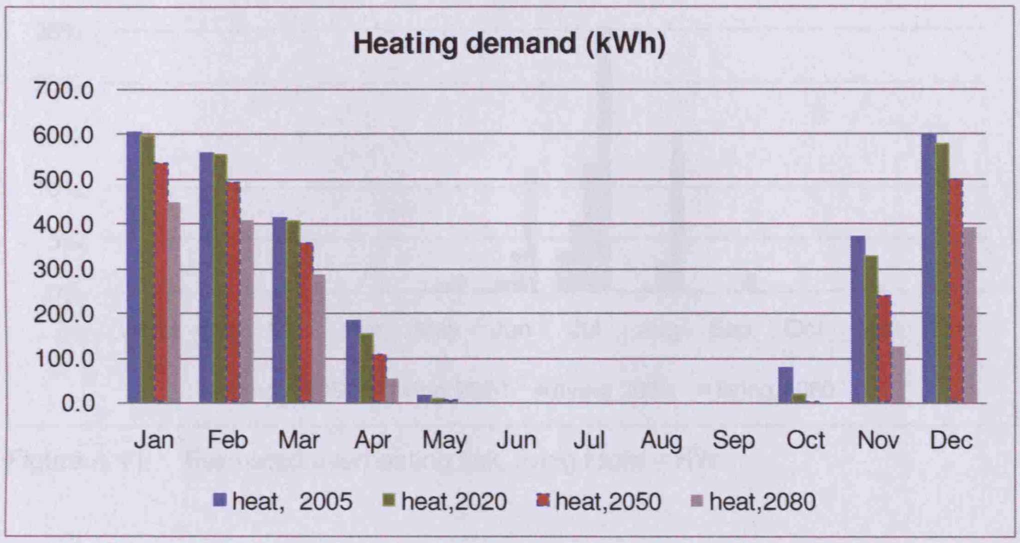


Figure A 9 Estimated heating demand – HW

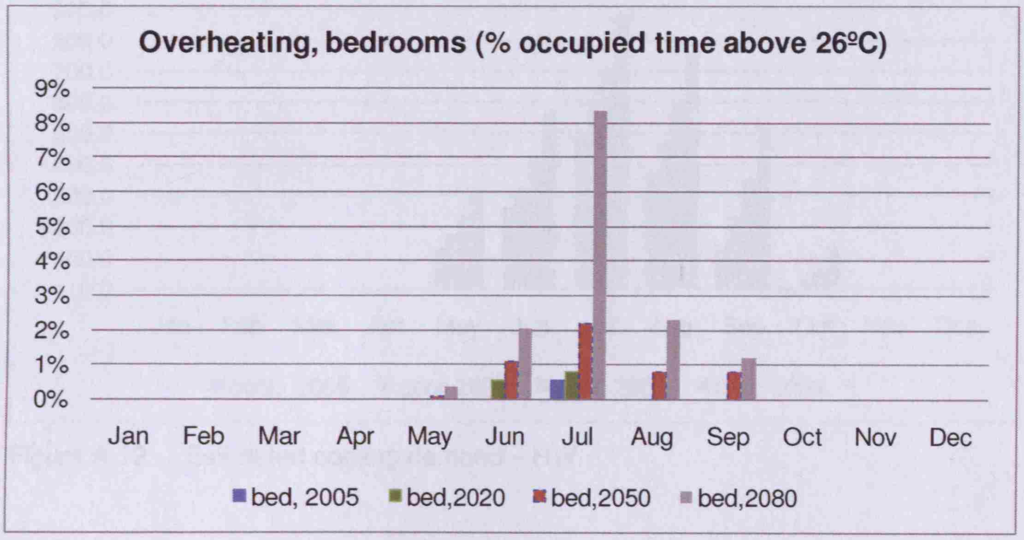


Figure A 10 Estimated overheating risk, bedrooms – HW

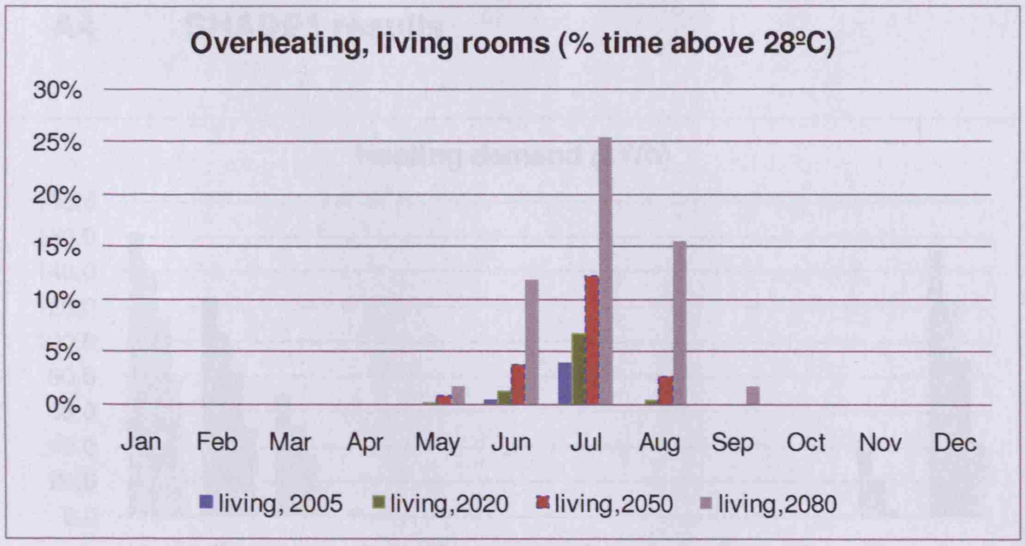


Figure A 11 Estimated overheating risk, living room – HW

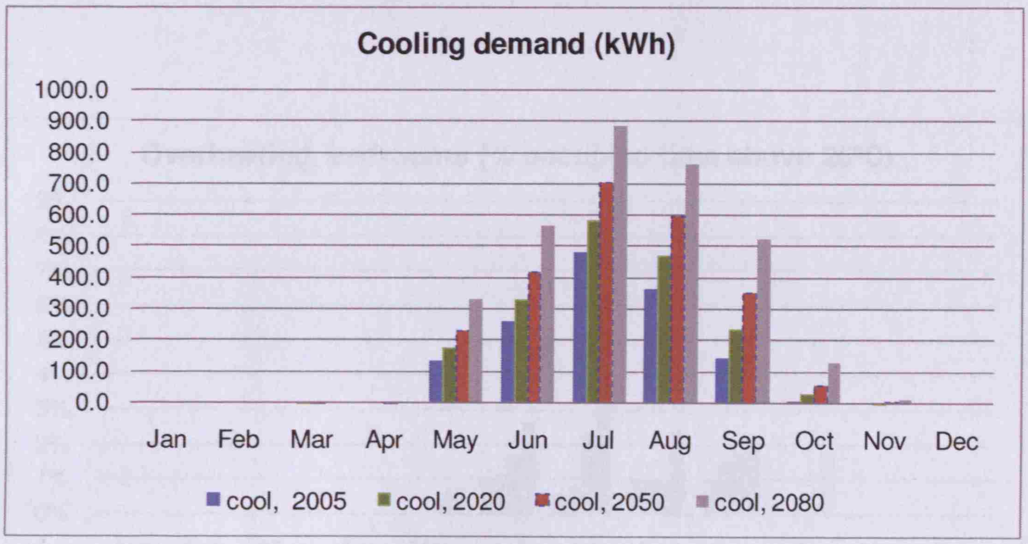


Figure A 12 Estimated cooling demand – HW

A4 SHADE1 results

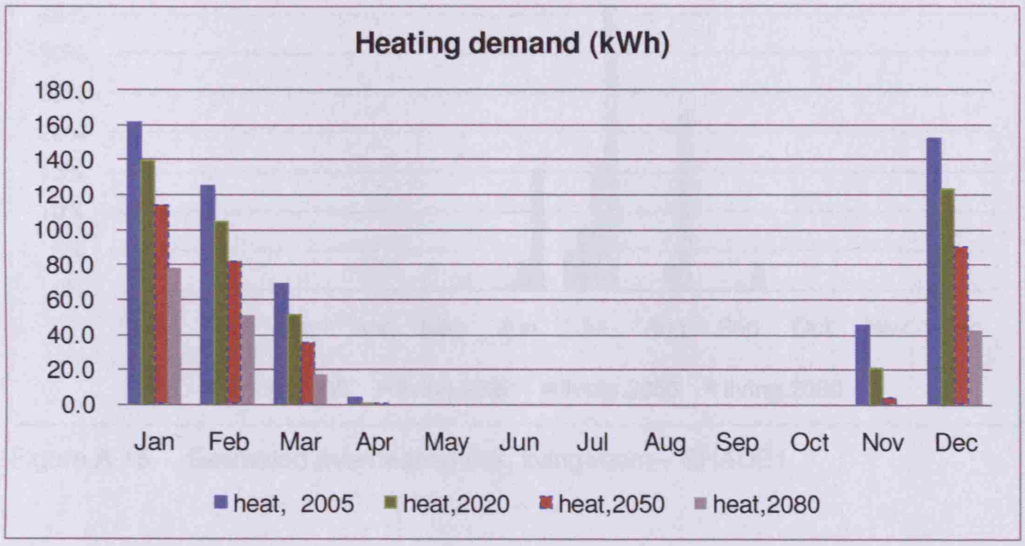


Figure A 13 Estimated heating demand – SHADE1

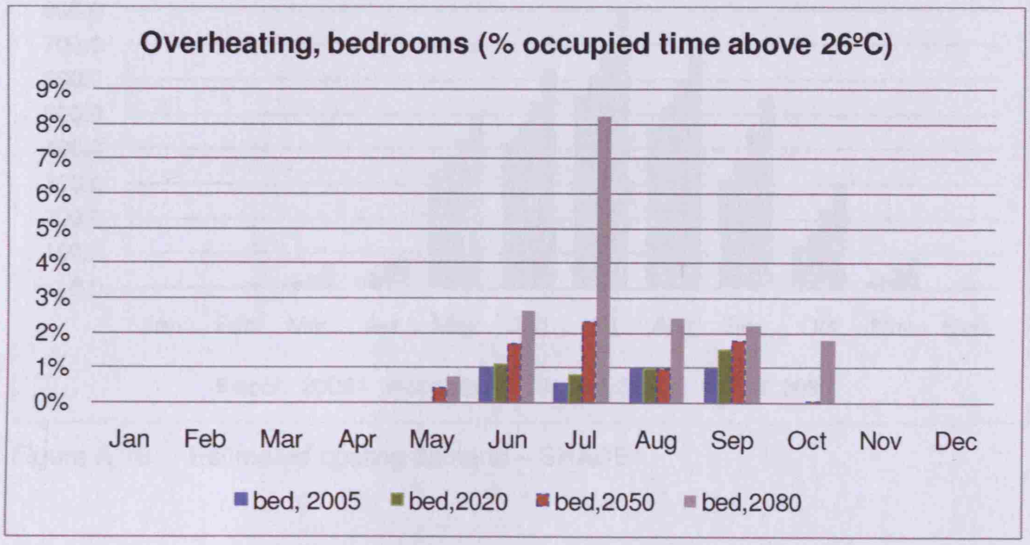


Figure A 14 Estimated overheating risk, bedrooms – SHADE1

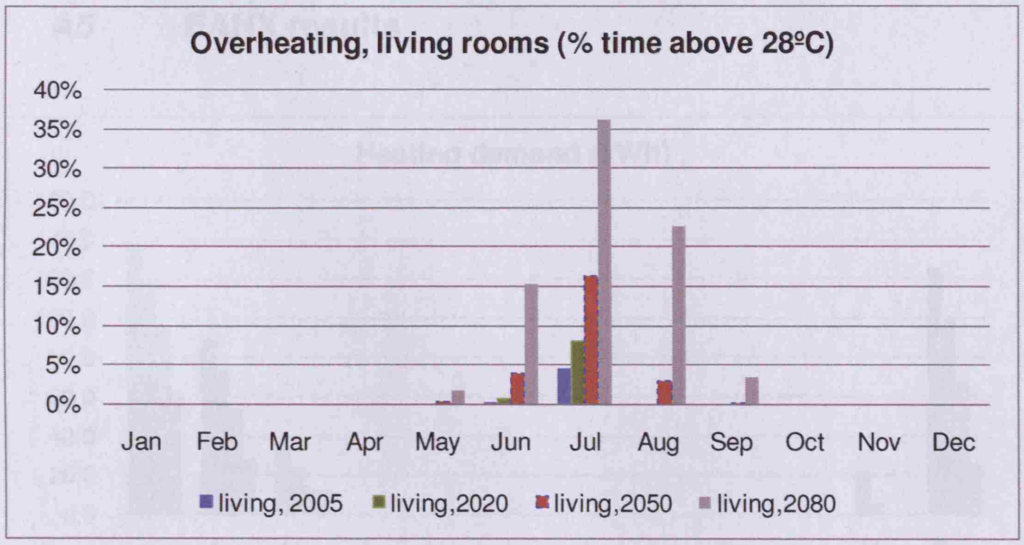


Figure A 15 Estimated overheating risk, living room – SHADE1

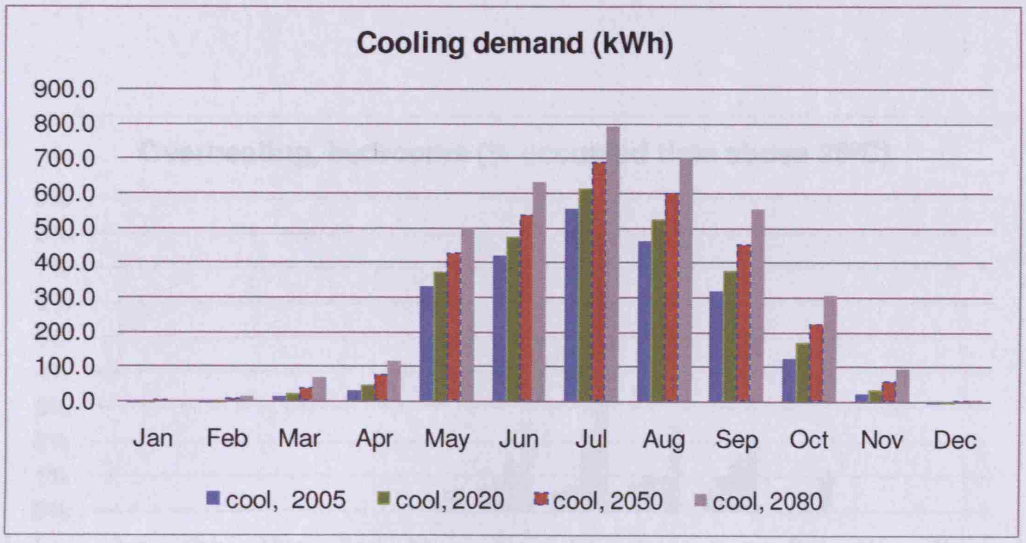


Figure A 16 Estimated cooling demand – SHADE1

A5 EAHX results

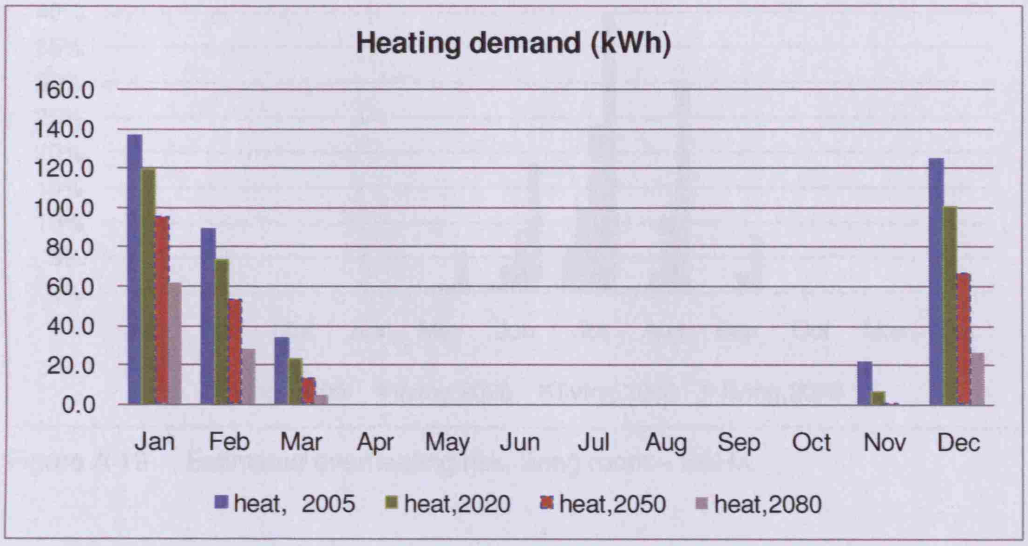


Figure A 17 Estimated heating demand – EAHX

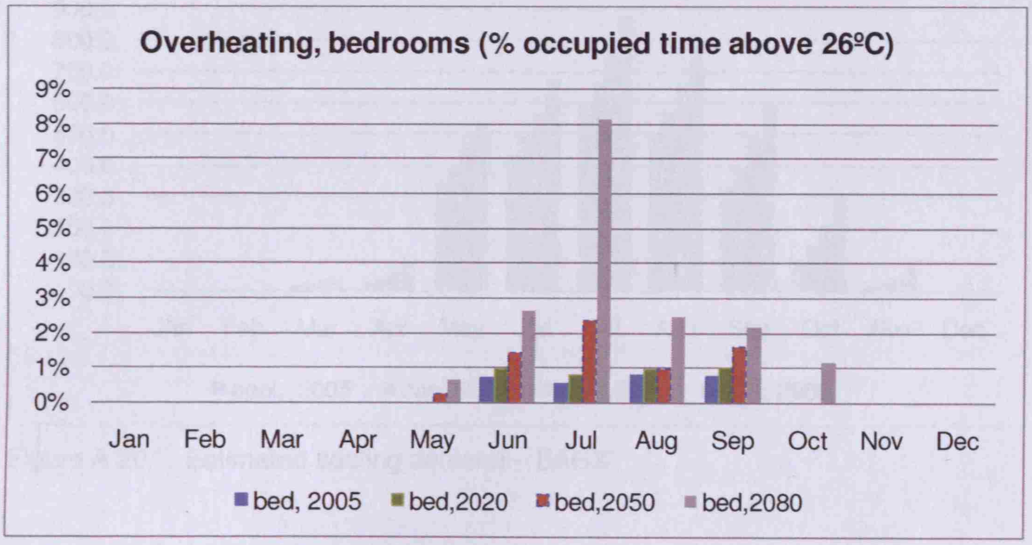


Figure A 18 Estimated overheating risk, bedrooms – EAHX

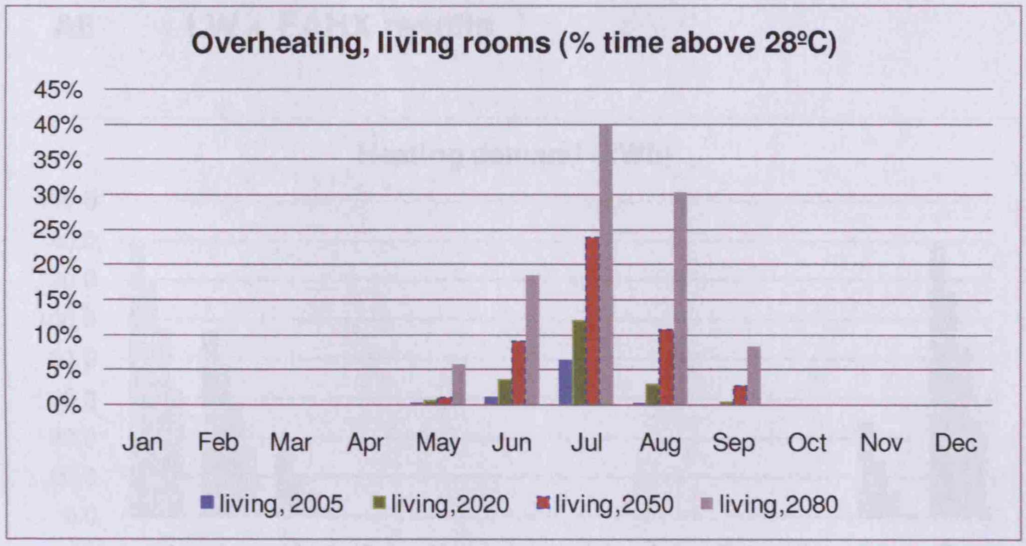


Figure A 19 Estimated overheating risk, living room – EAHX

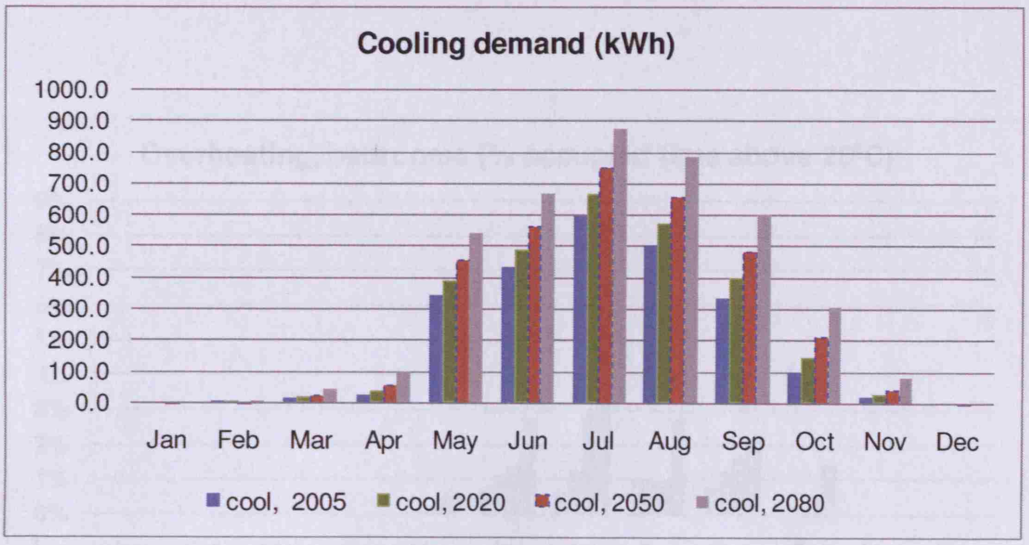


Figure A 20 Estimated cooling demand – EAHX

A6 LW + EAHX results

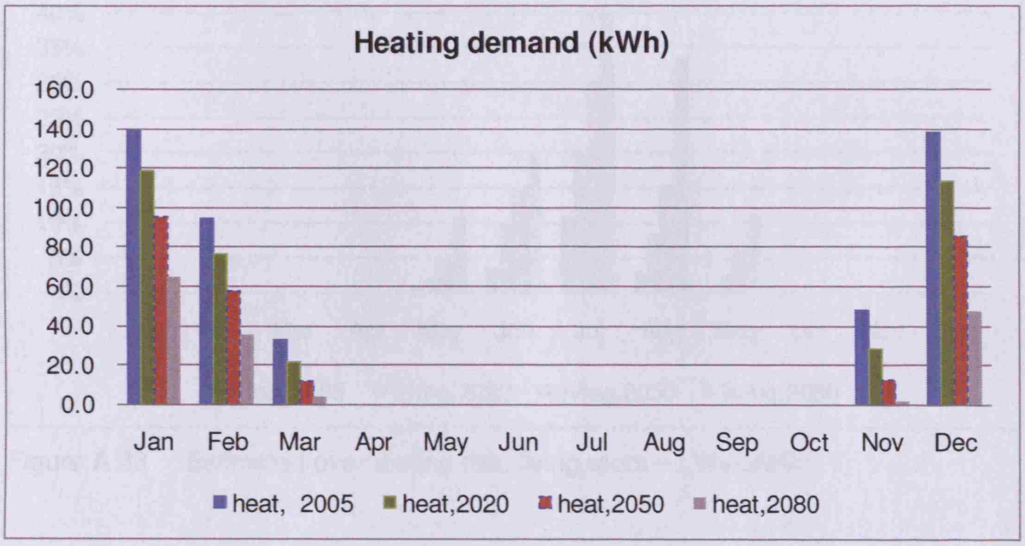


Figure A 21 Estimated heating demand – LW+EAHX

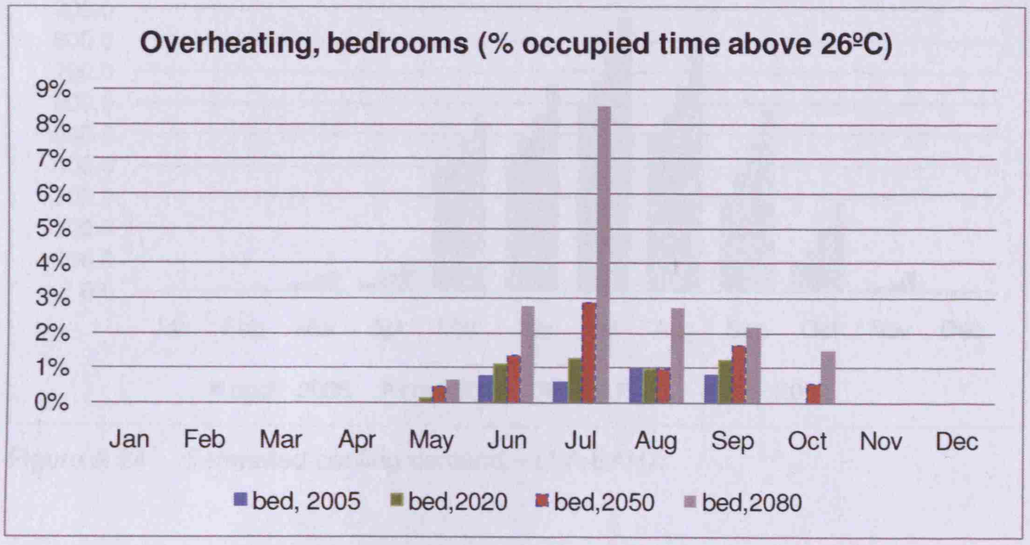


Figure A 22 Estimated overheating risk, bedrooms – LW+EAHX

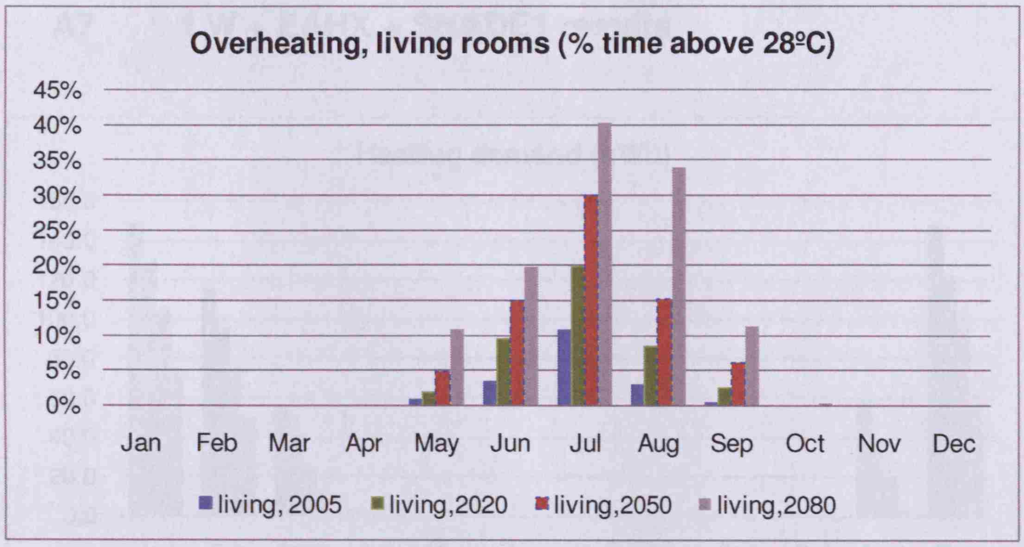


Figure A 23 Estimated overheating risk, living room – LW+EAHX

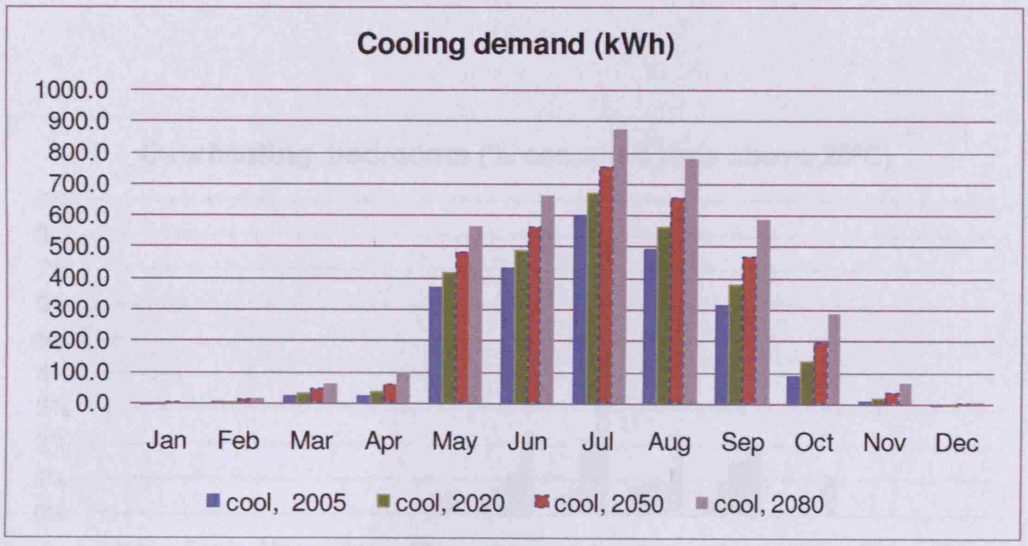


Figure A 24 Estimated cooling demand – LW+EAHX

A7 LW + EAHX + SHADE1 results

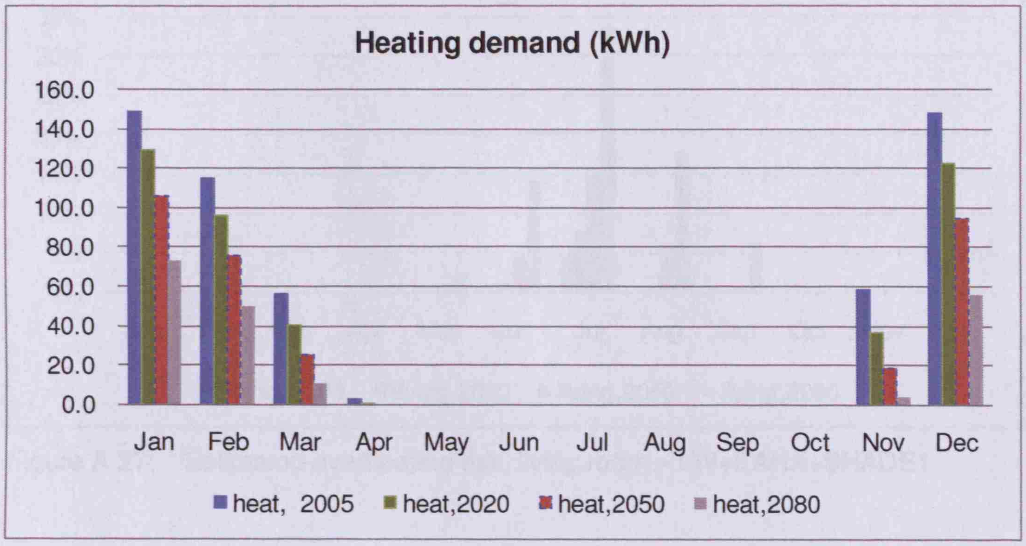


Figure A 25 Estimated heating demand – LW+EAHX+SHADE1

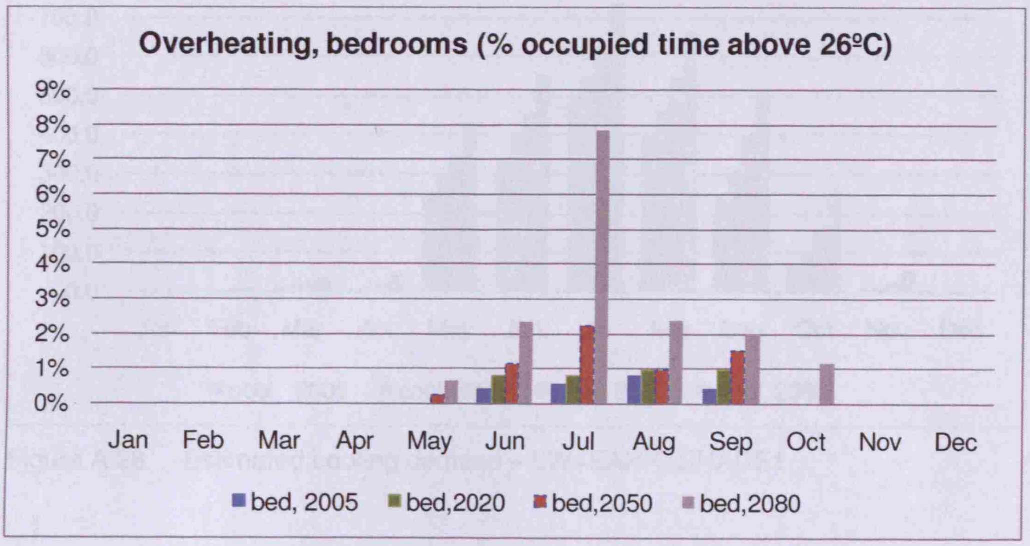


Figure A 26 Estimated overheating risk, bedrooms – LW+EAHX+SHADE1

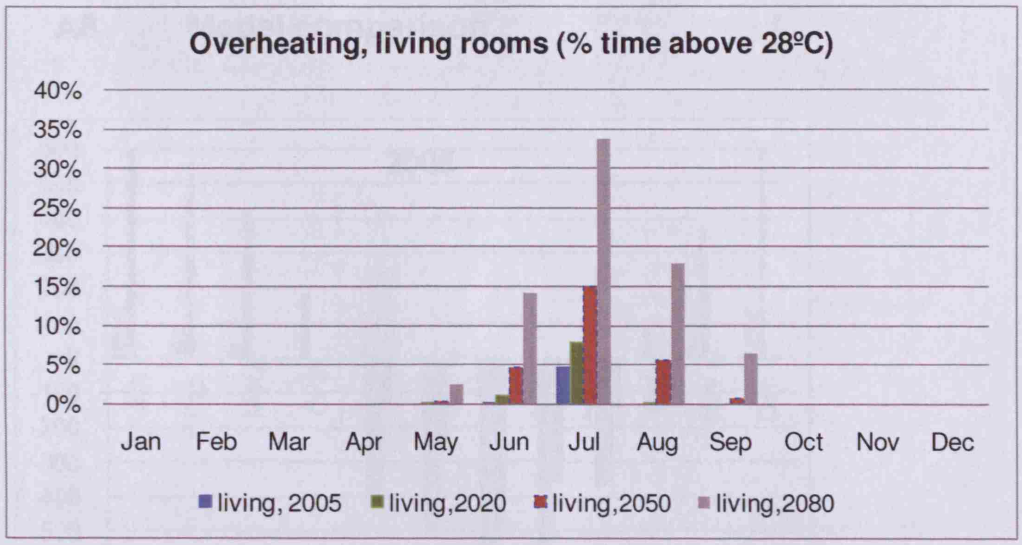


Figure A 27 Estimated overheating risk, living room – LW+EAHX+SHADE1

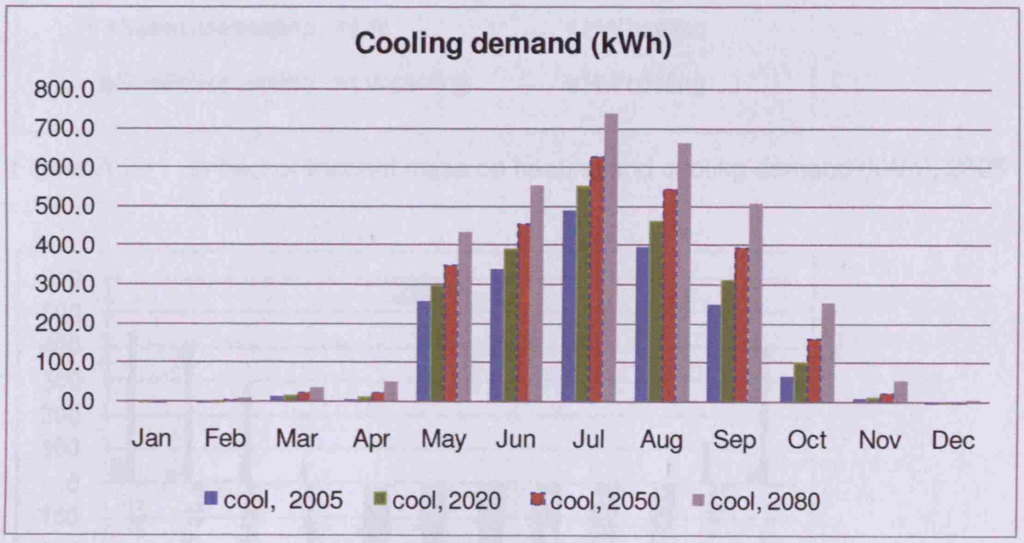


Figure A 28 Estimated cooling demand – LW+EAHX+SHADE1

A8 Model comparison

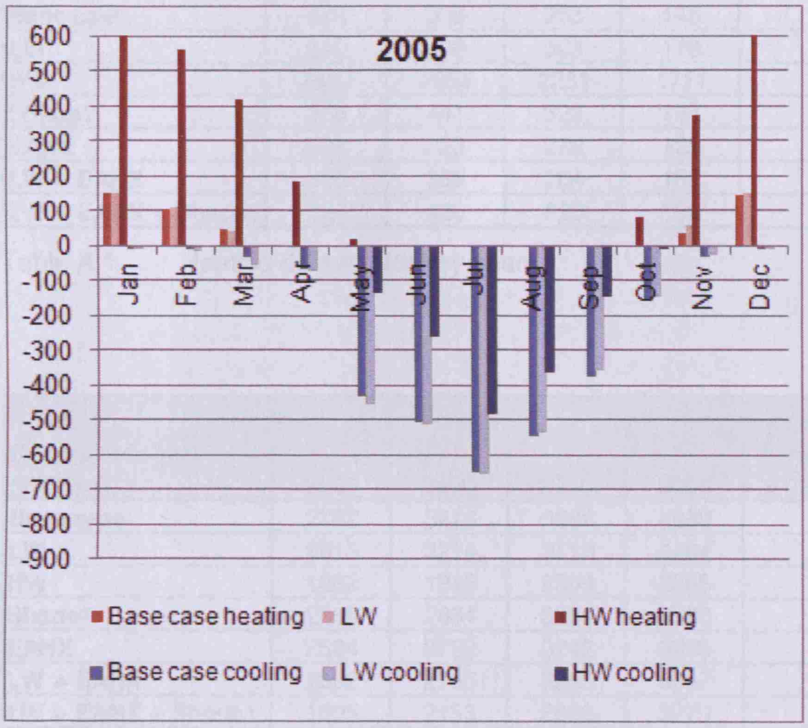


Figure A 29 Impact of thermal mass on heating and cooling demand (kWh), 2005

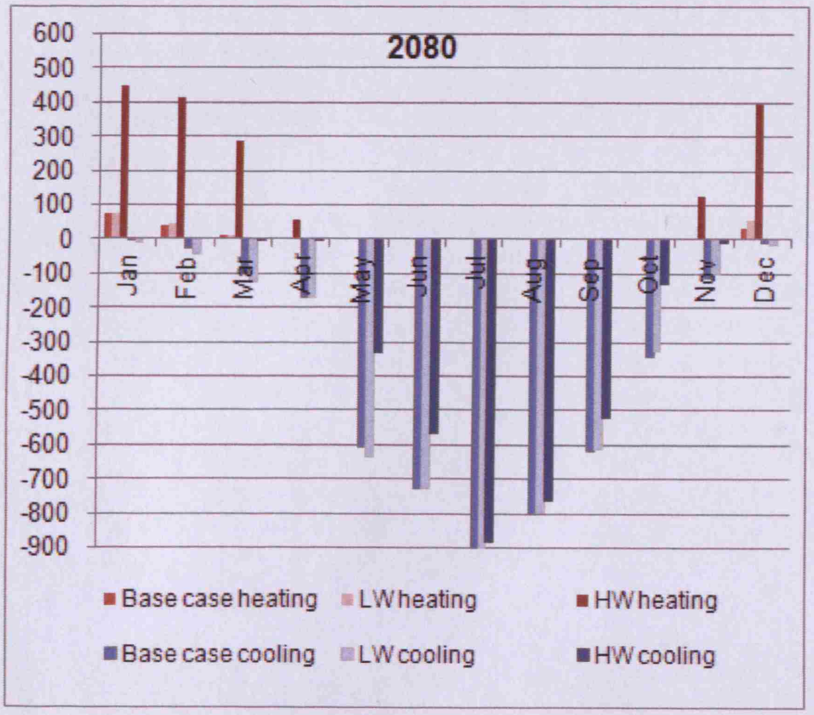


Figure A 30 Impact of thermal mass on heating and cooling demand (kWh), 2080

Heating demand (kWh/yr)	2005	2020	2050	2080	average heating demand 2010-2069
Base case	478	338	265	145	306
LW	510	408	303	178	360
HW	2830	2654	2231	1711	2441
Shade1	558	441	323	188	389
EAHX	406	323	228	120	280
LW + EAHX	453	359	264	152	316
LW + EAHX + Shade1	529	426	320	192	378

Table A 1 Heating demand for key years

Cooling demand (kWh/yr)	2005	2020	2050	2080	average cooling demand 2010 - 2069 *
Base case	2782	3414	3686	4439	3578
LW	2813	3214	3713	4464	3472
HW	1382	1813	2366	3205	2437
Shade1	2269	2634	3089	3780	3148
EAHX	2324	2722	3242	3996	2988
LW + EAHX	2362	2755	3255	4007	3015
LW + EAHX + Shade1	1805	2153	2602	3279	2659

* Calculated from year after overheating criteria are not met

Table A 2 Cooling demand for key years

A9 Embodied energy calculations

Embodied energy - base case								
Building element	**Area of building element (m2)**	**Type of material**	**Volume of material (m3/m2)**	**Total volume (m3)**	**Embodied energy (MWh/m3), from Table 13**	**Total embodied energy (MWh)**	**Embodied CO2 (tCO2/m3)**	**Total embodied CO2 (tCO2)**
External wall	78.1	softwood timber, 75mmx200mm studs @ 400mm c/c	0.038	2.93	3.77	11.05	0.22	0.66
		12.5mm plasterboard	0.013	0.98	2.59	2.53	0.23	0.22
Internal walls (incl. Party wall)	89.2	12.5mm plasterboard	0.013	1.12	2.59	2.89	0.23	0.26
		softwood timber, 50mmx100mm studs @ 400mm c/c	0.013	1.12	3.77	4.21	0.22	0.25
		12.5mm plasterboard	0.013	1.12	2.59	2.89	0.23	0.26
Ground floor	62.5	15mm terrazzo tile	0.015	0.94	3.36	3.15	0.28	0.27
		50mm screed	0.050	3.13	3.61	11.28	0.47	1.47
		200mm concrete	0.200	12.50	3.61	45.14	0.47	5.87
Upper floor	62.5	20mm softwood timber flooring	0.020	1.25	3.77	4.72	0.22	0.28
		150mm precast concrete	0.150	9.38	4.72	44.25	0.51	4.76
		15mm plaster	0.015	0.94	1.53	1.43	0.14	0.13
					Total	**133.53**	**Total**	**14.41**

Table A 3 Embodied energy & CO_2 – base case

Embodied energy - LW - light-weight structure (timber-framing)								
Building element	Area of building element (m2)	Type of material	Volume of material (m3/m2)	Total volume (m3)	Embodied energy (MWh/m3), from Table 13	Total embodied energy (MWh)	Embodied CO2 (tCO2/m3)	Total embodied CO2 (tCO2)
External wall	78.1	softwood timber, 75mmx200mm studs @ 400mm c/c	0.038	2.93	3.77	11.05	0.22	0.66
		12.5mm plasterboard	0.013	0.98	2.59	2.53	0.23	0.22
Internal walls (incl. Party wall)	89.2	12.5mm plasterboard	0.013	1.12	2.59	2.89	0.23	0.26
		softwood timber, 50mmx100mm studs @ 400mm c/c	0.013	1.12	3.77	4.21	0.22	0.25
		12.5mm plasterboard	0.013	1.12	2.59	2.89	0.23	0.26
Ground floor	62.5	20mm softwood timber flooring	0.020	1.25	3.77	4.72	0.22	0.28
		12.5mm plywood	0.013	0.78	8.25	6.45	0.41	0.32
		softwood timber, 50mmx200mm beams @ 300mm c/c	0.033	2.08	3.77	7.86	0.22	0.47
Upper floor	62.5	20mm softwood timber flooring	0.020	1.25	3.77	4.72	0.22	0.28
		softwood timber, 50mmx200mm beams @ 300mm c/c	0.033	2.08	3.77	7.86	0.22	0.47
		12.5mm plywood	0.013	0.78	8.25	6.45	0.41	0.32
		12.5mm plasterboard	0.013	0.78	2.59	2.03	0.23	0.18
					Total	61.61	Total	3.97

Table A 4 Embodied energy & CO_2 – LW

Embodied energy - HW - heavy-weight structure (concrete)								
Building element	Area of building element (m2)	Type of material	Volume of material (m3/m2)	Total volume (m3)	Embodied energy (MWh/m3), from Table 13	Total embodied energy (MWh)	Embodied CO2 (tCO2/m3)	Total embodied CO2 (tCO2)
External wall	78.1	150mm precast concrete wall	0.150	11.71	4.72	55.26	0.51	5.94
		15mm plaster	0.015	1.17	1.53	1.79	0.14	0.16
Internal walls (incl. Party wall)	89.2	15mm plaster	0.015	1.34	1.53	2.04	0.14	0.18
		150mm precast concrete	0.150	13.38	4.72	63.15	0.51	6.79
		15mm plaster	0.015	1.34	1.53	2.04	0.14	0.18
Ground floor	62.5	15mm terrazzo tile	0.015	0.94	3.36	3.15	0.28	0.27
		50mm screed	0.050	3.13	3.61	11.28	0.47	1.47
		200mm concrete	0.200	12.50	3.61	45.14	0.47	5.87
Upper floor	62.5	15mm terrazzo tile	0.015	0.94	3.36	3.15	0.28	0.27
		50mm screed	0.050	3.13	3.61	11.28	0.47	1.47
		150mm precast concrete	0.150	9.38	4.72	44.25	0.51	4.76
		15mm plaster	0.015	0.94	1.53	1.43	0.14	0.13
					Total	243.98	Total	27.47

Table A 5 Embodied energy & CO_2 – HW

Embodied energy - SHADE1 - shaded south glazing								
Building element	Area of building element (m2)	Type of material	Volume of material (m3/m2)	Total volume (m3)	Embodied energy (MWh/m3), from Table 13	Total embodied energy (MWh)	Embodied CO2 (tCO2/m3)	Total embodied CO2 (tCO2)
As base case	n/a	varies	n/a	n/a	Total	133.53	Total	14.41
Shading elements	14.0	3mm stainless steel profiles	0.004	0.06	412.00	23.07	49.20	2.76
					Total	156.60	Total	17.17

Table A 6 Embodied energy & CO_2 – SHADE1

Embodied energy - EAHX								
Building element	Area of building element (m2)	Type of material	Volume of material (m3/m2)	Total volume (m3)	Embodied energy (MWh/m3), from Table 13	Total embodied energy (MWh)	Embodied CO2 (tCO2/m3)	Total embodied CO2 (tCO2)
As base case	n/a	varies	n/a	n/a	Total	133.53	Total	14.41
EAHX pipe	n/a	40m of 250mm diam polypropylene pipe	n/a	0.22	75.96	16.71	1.800	0.40
					Total	150.24	Total	14.81

Table A 7 Embodied energy & CO_2 – EAHX

Embodied energy - alternative heavy-weight structure *(green concrete)*									
Building element	**Area of building element (m2)**	**Type of material**	**Volume of material (m3/m2)**	**Total volume (m3)**	**Embodied energy (MWh/m3), from Table 13**	**Total embodied energy (MWh)**	**Embodied CO2 (tCO2/m3)**	**Total embodied CO2 (tCO2)**
External wall	78.1	*150mm concrete wall, 60% GGBS **	*0.150*	*11.71*	*2.34*	*27.36*	*0.32*	*3.70*
		15mm plaster	0.015	1.17	1.53	1.79	0.14	0.16
Internal walls (incl. Party wall)	89.2	15mm plaster	0.015	1.34	1.53	2.04	0.14	0.18
		*150mm concrete, 60% GGBS **	*0.150*	*13.38*	*2.34*	*31.26*	*0.32*	*4.23*
		15mm plaster	0.015	1.34	1.53	2.04	0.14	0.18
					0.00	0.00	0.00	
Ground floor	62.5	15mm terrazzo tile	0.015	0.94	3.36	3.15	0.28	0.27
		50mm screed	0.050	3.13	3.61	11.28	0.47	1.47
		*200mm concrete, 60% GGBS **	*0.200*	*12.50*	*2.34*	*31.26*	*0.32*	*4.23*
					0.00	0.00	0.00	
Upper floor	62.5	15mm terrazzo tile	0.015	0.94	3.36	3.15	0.28	0.27
		50mm screed	0.050	3.13	3.61	11.28	0.47	1.47
		*150mm concrete, 60% GGBS **	*0.150*	*9.38*	*3.61*	*44.25*	*0.51*	*4.76*
		15mm plaster	0.015	0.94	1.53	1.43	0.14	0.13
					Total	**170.31**	**Total**	**21.04**

* 'Green concrete' conprises of 60% of the cement content replaced with GGBS, a waste product from the steel-making industry

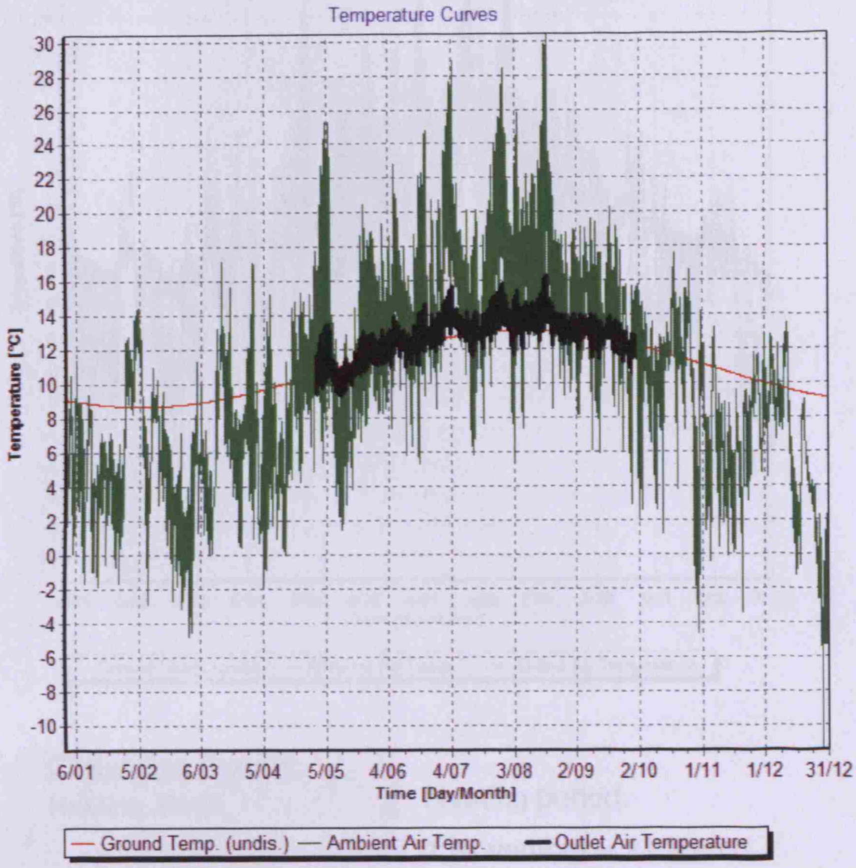
Table A 8 Embodied energy & CO_2 – HW with 'green concrete' alternative

Embodied energy - timber framing replacing stainless steel								
Building element	**Area of building element (m2)**	**Type of material**	**Volume of material (m3/m2)**	**Total volume (m3)**	**Embodied energy (MWh/m3), from Table 13**	**Total embodied energy (MWh)**	**Embodied CO2 (tCO2/m3)**	**Total embodied CO2 (tCO2)**
Shading elements	14.0	*stainless steel fixtures (assumed) **		*0.01*	*412.00*	*4.12*	*49.20*	*0.49*
	14.0	*average 50mm timber sections (assumption)*	*0.050*	*0.70*	*3.77*	*2.64*	*0.22*	*0.16*
					Total	**6.76**	**Total**	**0.65**

* It is assumed here that a minimum of stainless steel elements is necessary to fix the timber shading elements to the walls

Table A 9 Embodied energy & CO_2 – SHADE1 with timber

A10 EAHX calculation results



Calculation Results:

Cooling Mode

Max. Outlet Temperature [°C]:	16.3
Heating [kWh/a]:	61.0
Cooling [kWh/a]:	231.1
Net Cooling [kWh/a]:	-170.1
Air Velocity [m/s]:	0.82
Pressure Drop [Pa]:	3.58
Coeff. of Performance [-]:	-174.80

Cooling period:

1 May– 30 September

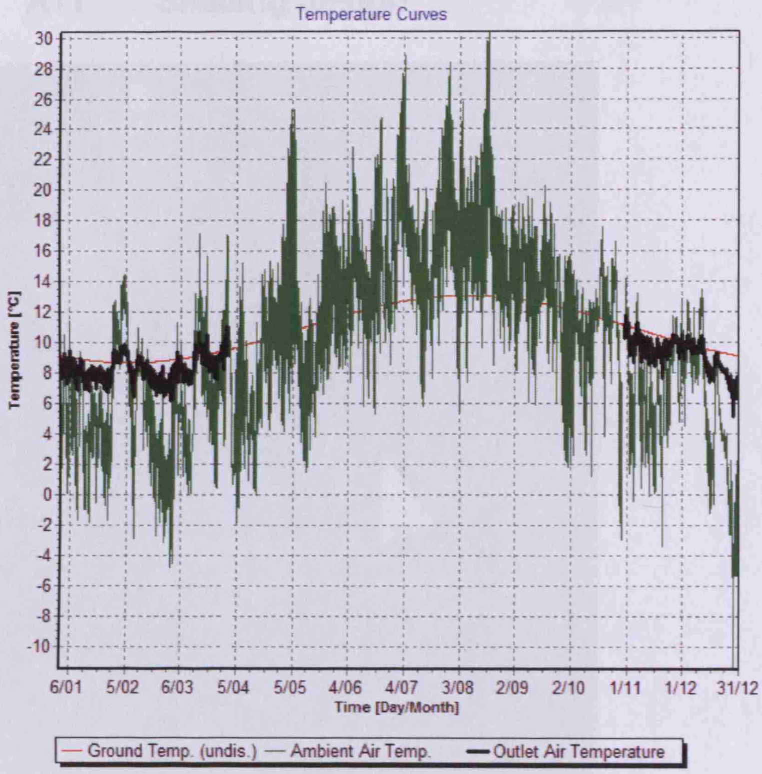
Air flow: $80m^3$/hour

40m pipe, 200mm diameter

Laying depth: 1.5m

Standard soil (sandy)

Figure A 31 EAHX calculation results – pre-cooling mode



Calculation Results:

Heating Mode

Min. Outlet Temperature [°C]:	5.5
Heating [kWh/a]:	362.4
Cooling [kWh/a]:	38.9
Net Heating [kWh/a]:	323.5
Air Velocity [m/s]:	0.82
Pressure Drop [Pa]:	3.56
Coeff. of Performance [-]:	280.92
Thermal Efficiency [%]:	19.41

Heating period:

1 November – 31 March

Air flow: 80m^3/hour

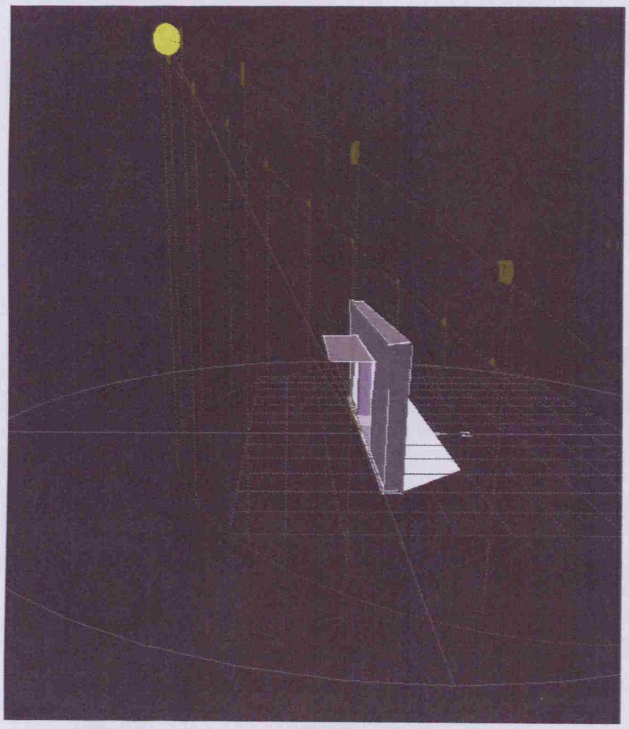
40m pipe, 200mm diameter

Laying depth: 1.5m

Standard soil (sandy)

Figure A 32 EAHX calculation results – pre-heating mode

A11 Shading design



Horizontal shading for 2300mm high windows, 1000mm-3000mm wide, 1200mm horizontal projection

200mm overhang each side

Effective Shading Coefficients

Latitude: 50.5°
Longitude: -0.5°
Timezone: -0.0° [-0.0hrs]
Orientation: 180.0°

Month	Avg.SC	Max.SC	Min.SC
January	8.3%	17.0%	0.0%
February	17.1%	29.0%	0.0%
March	27.1%	42.0%	0.0%
April	50.6%	70.0%	17.0%
May	69.9%	94.0%	42.0%
June	75.7%	100.0%	42.0%
July	66.5%	89.0%	34.0%
August	46.4%	65.0%	17.0%
September	24.3%	39.0%	0.0%
October	14.7%	23.0%	0.0%
November	7.8%	13.0%	0.0%
December	5.5%	12.0%	0.0%
Winter	10.3%	19.3%	0.0%
Summer	70.7%	94.3%	39.3%
Annual	34.5%	49.4%	12.7%

Figure A 33 Shading layout and shading coefficients

A12 SAP calculation results

DESIGN INPUT & RESULTS

Users Ref: passivhaus

Issued on: 3.August.2008
Prop Type Ref: Dolcoath

Property: Passivhaus Hannover Kronsberg, London

TER: 21.65
DER: 8.41

SAP Rating: 89 B	**SAP Energy Cost:** £176	**CO2 Emissions:** 0.84 t/year			
EI Rating: 93 A	**Energy used:** 60 kWh/m2/year	**Enel:** 0	**ZC:** 0.00		

Surveyor: 0000-0000, Unaccredited Surveyor
Address:
Client:

Software Version: EES SAP 2005.015.build.0019, April 2008 (Design System), BRE SAP Worksheet 9.81
Regs Type: SAP 2005, Regs Region: England and Wales (Part L1A 2006), Construction Type: New Build

SUMMARY OF INPUT DATA FOR DWELLING AS DESIGNED: Page 1 of 2

Region & Orientation	Region: SE South East (16), House Orientation: N North
1.0 Property Type	H House, E End Terrace
2.0 Number of Storeys	2
3.0 Date Built	2008
4.0 Sheltered Sides	1
5.0 Sunlight/Shade	Average or unknown
6.0 Internal Walls Perimeter	22.70 m, 22.70 m
7.0 Internal Floor Area	60.00 m2, 59.90 m2
8.0 Living Area	42.00, fraction: 0.35
9.0 Average Storey Height	2.60 m, 2.75 m
9.1 Conservatory	None

General Requirements (new build only)
! Inadequate Solar cylinder

Openings	Description	Glazing Type	Solar Trans	Frame or Door Type	Air Gap	Argon Fill	Orientation	Uvalue	Area
10.0 Ext. Doors	door	Triple glazed	0.68	Glazed Wood	16 mm	No		0.83 (M)	2.30
		Draught Lobby							
11.0 Windows	window s	Triple glazed	0.68	Wood	12 mm	Yes	South (180°)	0.83 (M)	11.50
	window n	Triple glazed	0.68	Wood	16 mm	Yes	North (0°)	0.83 (M)	6.40

Openings Average: U: 0.83

Uvalue legend: (T) = Uvalue defaulted from SAP Table (M) = Manufacturer supplied

13.0 Draught Proofing	100%
14.0 Thermal Bridging	User Input
Thermal Bridges Y	0.020 Description passivhaus
15.0 Pressure Test (q50)	Air permeability 0.20 $m^3/h.m^2$ (assumed)
16.0 Mechanical Ventilation	Balanced mechanical ventilation with heat recovery, WholeHouse_MVHR, Duct: Rigid, from data sheet, SFP 0.80 W/(l/sec), Heat recovery efficiency 0.8
17.0 Fans, Chimneys, Flues	0, 0, 0
17.1 Lighting	Light fittings: 10, L.E.L. fittings: 10, External lights: Yes, controlled: Yes

	Description	U-value	Shelter	Room in Roof	Area	Timber	Curtain Walling
18.0 Wall Types	wall	0.13	0.00		101.24 (X)	Yes	No
	Walls uvalue average: U: 0.13						
	Timber or Steel frame area				101.24		
19.0 Plane Roofs	Roof roof	0.10			60.00 (X)		
	Roofs uvalue average: U: 0.10						
20.0 Ground Floor Types	floor	0.13			60.00 (X)	No	
	Floors uvalue average: U: 0.13						

20.1 Thermal Mass	Simple Thermal Mass Parameter calculation: Ground Floor Mass: Low - suspended timber floor External Wall Mass: Low - timber/steel frame walls or masonry walls (internal insulation) Separating Wall Mass: Low - plasterboard on timber/steel stud Internal Partition Mass: Low - plasterboard on timber/steel stud
20.2 Fixed Air Conditioning	No
21.0 Main Heating	Manufacturer's data: tbc, Pumped: pump in heated space
MHS Efficiency	Manufacturer data: 75.0%
Manufacturer & Model	Manufacturer's data: tbc, tbc, 75.0%
Heating Controls	CCD Unit charging, programmer and TRVs Boiler interlock - Yes
Underfloor Heating	None

DESIGN INPUT & RESULTS

Users Ref: passivhaus		**Issued on:** 3.August.2008	
		Prop Type Ref: Dolcoath	
Property: Passivhaus Hannover Kronsberg, London		**TER:** 21.65	
		DER: 8.41	
SAP Rating: 89 B	**SAP Energy Cost:** £176	**CO2 Emissions:** 0.84 t/year	
EI Rating: 93 A	**Energy used:** 60 kWh/m2/year	**Enel:** 0	**ZC:** 0.00

Surveyor: 0000-0000, Unaccredited Surveyor
Address:
Client:

Software Version: EES SAP 2005.015.build.0019, April 2008 (Design System), BRE SAP Worksheet 9.81
Regs Type: SAP 2005, Regs Region: England and Wales (Part L1A 2006), Construction Type: New Build

SUMMARY OF INPUT DATA FOR DWELLING AS DESIGNED: Page 2 of 2

21.1 Secondary Heating	None
SHS Details	
22.0 Hot Water Heating	HWP From the primary heating system
Solar Water Heating	Solar panel: Yes, gross area: 3.80 m2, Type: Flat plate, glazed Collector zero-loss efficiency: 0.75 Collector heat loss coefficient: 6.00 Solar panel ratio A/G: 0.90 Orientation: South, Elevation: 30°, Overshading: None or little (< 20%) Solar powered pump, ! No Solar Cylinder
23.0 Thermal Store	None
24.0 Hot Water Cylinder	Yes, in unheated space
Insulation	Foam, Thickness: 150 mm
Volume	300.00 litres, Cylinder contains dedicated solar storage
25.0 Community Heating	Yes, Distribution loss: 4 Pre-insulated piping >1990, low temperature <= 100
CHP Unit	Fuel: G Mains Gas Fraction of Heat: 100.00% Overall Efficiency: 70.00% Heat/Power ratio: 1.50 Electrical Efficiency: 28.00% Heat Efficiency: 42.00%
26.0 Electricity Tariff	P - 10 Hour Off Peak
27.0 Photovoltaic Unit	None
27.2 Micro Wind Turbines Count	0
Rotor Diameter	0.00
Hub Height	0.00
Terrain Type	Urban
27.3 Small-scale Hydro electricity	0.00
28.0 Special Features	None